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The Effects of Fire on Sonoran Desert Plant Communities

Final Report

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The Adaptation of Sonoran Desert Vegetation to Wildfire on the Tonto National Forest
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ABSTRACT

The effects of fire on Sonoran Desert plant communities were determined by analyzing the influence of anthropogenic and climatic factors on fire regimes and measuring the responses of plants on a time-since-fire (tsf) gradient.

An upward trend in the number of fires has occurred during the past 45 years in the Sonoran Desert; however, there was not a significant ($P < 0.05$) trend in hectares burned. The positive trend in number of fires was consistent with an increase in the population of Maricopa County and an increase in traffic along major Sonoran Desert highways in the Tonto National Forest. The number of hectares burned did not change with increased winter, summer, spring, fall or total annual precipitation. However, the number of fires and hectares burned increased with increased precipitation from two and three consecutive winters' precipitation. Traffic and three consecutive winters' precipitation had the strongest coefficients in predicting the number of fires in the Sonoran Desert, yielding the model: y (number of fires) = $-49.166 + .0066x_1$ (traffic) + $.148x_2$ (three consecutive winters' precipitation). The best prediction model for hectares burned (y) was: $y = -2335.606 + 9.137x$ (three consecutive winters' precipitation).

Overall plant density decreased as canopy cover increased on a tsf gradient. Native species most impacted by fire were saguaro (*Carnegiea gigantea*) and foothill paloverde (*Cercidium microphyllum*). Foothill paloverde appeared to have recovered, with respect to density and canopy cover, in the years after the Siphon Fire (15–20 tsf). Repeated fires in the Bush Highway study plots have caused an increase in density for purple three-awn (*Aristida purpurea*) and desert senna (*Cassia armada*) and a decrease in native species such as saguaro, foothill paloverde, white ratany (*Krameria grayi*), wolfberry (*Lycium spp.*), and creosote bush (*Larrea tridentada*). No difference in production of red brome (*Bromus rubens*) was found between burned and control plots during the spring of 1998.

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CHAPTER 1

ECOLOGY OF THE SONORAN DESERT

Geographical Description of the Sonoran Desert

The Sonoran Desert is an arid, subtropical region that occupies ca. 275,000 km^2 in Northwestern Mexico and Southwestern United States (Shreve and Wiggins 1964, MacMahon and Wagner 1985, Smith et al. 1997). It is centered in the state of Sonora, Mexico and extends northward to central Arizona, USA (ca. 34°N), southward to the southern tip of the Baja Peninsula, Mexico (ca. 23°N), westward to Deep Canyon, California, USA (ca. 117°W), and eastward to the foothills of the Sierra Madre Occidental in Sonora, Mexico (ca. 109°W). In the interior of Mexico, the Sonoran Desert extends southward to the vicinity of the Río Yaqui, Sinoloa (Shreve 1951, Shreve and Wiggins 1964, Turner 1994; MacMahon 1979). Elevations range from below sea level in the Imperial Valley of California and 278 m at Needles, on the Colorado River, to ca. 1000 m at the northern margin (Turner and Brown 1982).

Influenced by subtropical climatic conditions, an extensive latitudinal and longitudinal range and diurnal rainfall, the Sonoran Desert supports a complex biota. In order to describe the diverse areas, Shreve (1951) divided the Sonoran Desert into seven subdivisions: (1) the Lower Colorado River Valley of western Arizona, southeastern California, and northwestern Sonora; (2) the Arizona Upland of central Arizona and northern Sonora; (3) the Plains of Sonora, in southern Sonora; (4) the Foothills of Sonora, extending from the vicinity of Arizpe, on the Río Sonora, southward to the delta of the Río Yaqui; (5) the Central Gulf Coast of coastal Sonora-Sínalola and the central Gulf Coast of Baja; (6) the Vizcaíno Region of west-central Baja; and (7) the Magdalena Region of southwestern Baja (Shreve and Wiggins 1964, Fig. 1.1).

The delineation of the subdivision boundaries of the Sonoran Desert has been scrutinized by some geoecologists since their formalization by Shreve (1951). The Mexican portion of the Sonoran Desert has been broadly interpreted to include northern Sinaloa, most of Sonora, and the peninsula of Baja California, or narrowly interpreted to include a coastal strip from west-central Sonoran to the Colorado River delta (Schmidt 1989, Burquez et al. 1999).

There seems to be general agreement on the delineation of the northern boundaries of the Sonoran Desert that is largely determined by winter freezing (Shreve 1951, Steenbergh and Lowe 1977, Crosswhite and Crosswhite 1982, Turner and Brown 1982). However, the delineation to the south and east has been problematic because the absence of major environmental discontinuities have allowed populations to disperse independently of each other and for communities to merge seamlessly (Búrquez et al. 1999). For example, the vegetation composition in the southern desert edge are similar to those of tropical deciduous forest, but individual species of trees and shrubs are often much smaller and different in growth form in the desert.

Turner and Brown (1982), extended and refined the work completed by Shreve (1951) and modified the major subdivision boundaries. They considered the foothills of Sonora and parts of the Magdalena region as Sínaloan thornscrub. The subunit boundaries as modified by Turner and Brown (1982) have been widely accepted by geoecologists. However, the Nature Conservancy included only the Lower Colorado River Valley, Arizona Upland, Plains of Sonora and Central Gulf Coast in their ecological analysis of the Sonoran Desert Ecoregion (Marshall et al. 2000). They concluded that the Foothills of Sonora, Vizcaíno and Magdalena Plains were more representative of the thornscrub vegetative type rather than a Sonoran Desert vegetative type.

Climate of the Sonoran Desert

The primary climatic factors that characterize the Sonoran Desert are warm temperatures and low precipitation (Schmidt 1989, Turner et al. 1995, Burquez et al. 1999). Annual precipitation is highly variable, summers are very hot, winters are mild, day/night temperature variations are great, and the solar radiation levels are high. Mean annual rainfall in the Sonoran Desert ranges from less than 30 mm near the Colorado River Delta to more than 350 mm at the eastern desert margin in the Arizona Upland Subdivision (Hastings and Turner 1965, Schmidt 1989). The

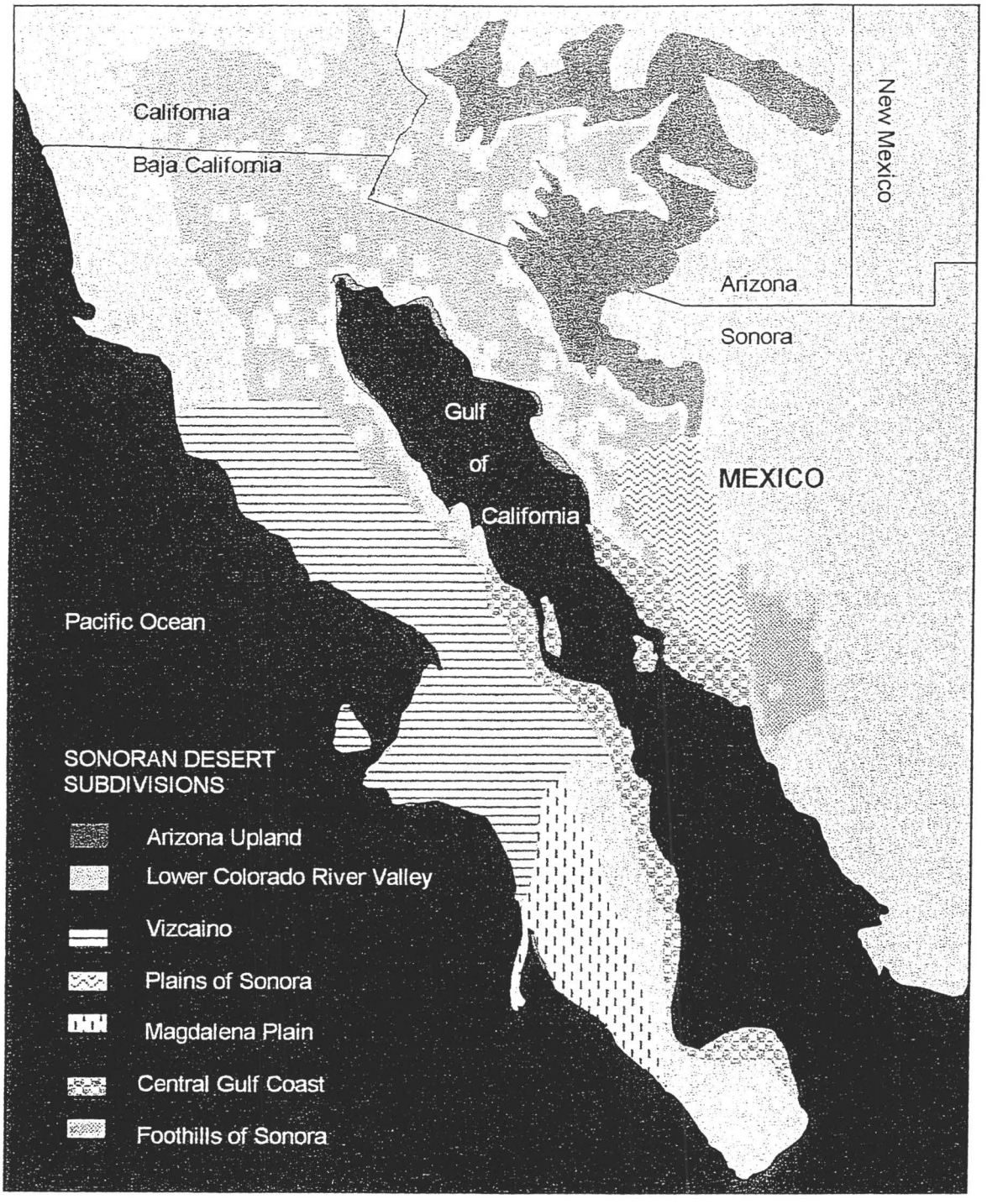


Fig. 1.1. Location of the Sonoran Desert and Subdivisions

amount of precipitation is influenced by rain shadows caused by the western cordillera blocking moisture from the Pacific Ocean origin in the winter and the eastern cordillera locking moisture from the Gulf of Mexico in the summer. Low precipitation is also influenced by the presence of a subtropical high-pressure cell, and cold currents along most of the western coast (Moran and Morgan 1997, Smith et al 1997). Regional air mass dynamics result in west-to-east frontal systems from the Pacific in the winter, then east-to-west and south-to-north convective air masses of subtropical origin in the summer. As a result, the Sonoran Desert is influenced by a summer-winter bimodal rain pattern (Turner 1994). Rainfall totals and seasonality generally form a southeast-to-northwest gradient. Annual totals generally increase from west to east. Summer rains contribute more than half the precipitation in the eastern portion of the desert, decreasing in percentage as one moves west (Burquez et al. 1999). Rainfall normally begins in the southeastern portion of the desert in late June, while in the western portion rains seldom begin until well into July. Rainfall is more reliable in the southeastern Sonoran Desert than in the northwestern part.

Temperature extremes in the Sonoran Desert generally form a gradient from north to south. The greatest extremes occur in northwestern Sonora, where summer highs frequently exceed 49°C and winter lows occasionally fall below freezing. The southern limit of periodic, damaging freezes establishes the northern limits of many Sonoran Desert plant species (Shreve 1951, Hastings and Turner 1965, Steenbergh and Lowe 1977, Bowers 1980, Nobel 1980, Turner et al. 1995).

The climatic extremes become more moderate in the southern coastal plains and foothills in Sonora. Frosts seldom occur south of the plains of the Río Sonora, temperatures are milder, humidity increases, and summer rainfall provides the bulk of annual precipitation (Burquez et al. 1999). Similarly, maritime influences ameliorate the aridity of the Baja California peninsula, the Gulf islands, and a narrow band along the coast of Sonora. In these areas, the ocean and maritime fog moderates temperatures.

The season and duration of precipitation are especially important factors influencing the available moisture to Sonoran Desert biota, because of very high evapotransporation rates. The potential evapotransporation is estimated to reach 2000 mm $year^{-1}$ (Evenari 1985) while the average annual precipitation in the Arizona Upland Subdivision is only 317 mm (Turner 1994). Although the bimodal rain pattern provides precipitation both in the winter and summer, the evaporation in the dry spring season exceeds the amount of precipitation during the moist winter. Similarly, soil moisture is low during the dry month of June and remains low even after summer rains because of very high potential evapotransporation.

Geomorphology of the Sonoran Desert

The most prominent features of the Sonoran Desert are those of the Basin and Range Province (Fenneman 1931, Burquez et al. 1999), a region of many parallel fault-block mountains interspersed by drainage basins formed by tectonic actions. Extensive low foothills with external, intermittent drainages characterize much of the Sonoran Desert. Alluvial fans, called *bajadas*, are large, coalesced, smooth slopes that accumulate outwash particles from adjacent mountains (McAuliffe 1994). In the Arizona Upland Subdivision of the Sonoran Desert, *bajadas* range in slope from ca. 1° near their lower boundary with plains or *playas* to 6-9° at their boundary with the foothills (MacMahon and Wagner 1985, Smith et al. 1997). Fluvial processes along slope-*bajada*-*playa* gradients result in course-textured materials being deposited on slopes and upper *bajadas* and progressively finer-textured materials being deposited towards the lower *bajadas* and *playas* (Phillips and MacMahon 1978, Smith et al. 1997). Soil textural differences are important because course-grained soils have higher water infiltration rates, but lower water holding capacities (Nash et al. 1991).

Desert pavement, which consists of a single, closely packed or a cemented layer of small soil particles, plays an important role in the spatial zoning of Sonoran Desert plants. A dark brown varnish, composed of clays and oxides of manganese and iron, is often deposited on the rock surfaces through bacterial action (Dorn and Oberlander 1981, Smith et al. 1997). The cemented

varnish surface, in concert with the sodic nature of the soil, results in a low infiltration rate of 0.8 cm h^{-1} on the pavement surface versus 9.6 cm h^{-1} on the adjacent non-pavement surface (Musick 1975). On *bajadas* with well-developed desert pavement, infiltration of water may be largely restricted to the vicinity of individual shrubs or shrub mounds (McAuliffe 1994, Smith et al. 1997). The shrub canopy (Price and Reichman 1987) and animal burrows (Elkins et al. 1986, Laundre 1993) enhance infiltration in these areas. Shrubs accumulate fine sediments within their canopy zones and also dissipate the kinetic energy of raindrops, whereas in inter-shrub areas fine sediments are selectively removed by rain splash and overland flow leaving behind a cemented surface of stones and gravel with poor infiltration (Abrahams and Parsons 1991). The resulting desert pavement is often harder than the rest of the soil because compounds such as salts, lime, and silica are deposited at the surface as water evaporates. Along with the hard surface restricting growth of certain flora, the high sodium content of desert pavement may prevent the establishment of many glycophytic (plants that grow only in soil that has more than 0.5% sodium chloride solution) desert taxa (Belnap 1995).

Belnap et al. (1999) contended that the bare spaces between the higher plants in the Sonoran Desert are generally not devoid of autotrophic life, but are covered by communities of highly specializes organisms. The soil surface floral community consists of cyanobacteria, green algae, lichens, mosses, microfungi, and bacteria. Cyanobacterial and microfungal filaments weave throughout the top few millimeters of soil, aggregating loose soil particles and forming biological crusts, which stabilize and protect soil surfaces from erosive forces (Cameron 1966; Freidmann and Galun 1974, Freidmann and Ocampo-Paus 1976, Belnap and Gardner 1993). The biological crusts are also referred to as cryptogrammic, cyptobiotic, macrobiotic or micorphytic soil crusts (Harper and Marble 1988, West 1990). Belnap (1995) also reported crusted soil surface temperatures in a Utah desert were more than 23° C warmer than adjacent uncrusted surfaces. This is because the darker surface, which is characteristic of the crusted soils, causes reduced albedo and increased energy absorption.

History of Sonoran Desert Biota

Changes in climate

Paleontological studies have revealed spatial and temporal dynamics of biota in the Sonoran Desert region in response to climate change. These studies describe a movement of the Sonoran Desert vegetation through geologic time from south to north on a moisture and temperature gradient. Tables 1.1 and 1.2 summarize the geological time scale and the changes in vegetation with geological time in the Sonoran Desert.

During the Wisconsin period (the final stage of the Pleistocene epoch 21 to 11 thousand years ago (kya), Table 1.2), climate changed from full-glacial (21kya) to inter-glacial (present) (Gates 1993). Massive ice sheets covered parts of North America and Europe 21kya and sea ice extended at least 10 degrees of latitude closer to the equator than it now does. The glaciations that occurred in the continental and montane areas did not occur in the Sonoran Desert region; however, the secondary effects of the ice sheets on global thermal circulation of the atmosphere were readily observed in the subtropical Sonoran Desert. In his work with a General Climate Model (GCM), Gates (1993) reported that a 3 km thick ice sheet in North America (18kya) caused the winter jet stream to divide into a strong westerly flow aloft north and south of the ice. The simulated temperatures over the land were much lower than at present, especially over the ice sheets. Strong anticyclonic circulation over the Laurentian ice sheet brought cold air to the North Atlantic south of the ice. This resulted in dry conditions in the American Northwest, where lake levels were very low. Farther south, westerly flows brought moist Pacific air over the land and generated the high lake levels found in the proxy records (Axelrod 1948, 1979, Gates 1993, Martin 1999, Van Devender and Spaulding 1979). Rapid melting of the glaciers took place between 15 and 12 kya as solar insolation increased and conditions warmed (Gates 1993, Martin 1999). In general, there was a strong summer cooling and a shift to winter precipitation (Van Devender 1990), The cooling in winter might have been offset reducing frequencies of catastrophic freezes (Van Devender 1990).

Table 1.1. Geologic time scale (Van Devender 2000).

EON	ERA	PERIOD		EPOCH	TIMESPAN
Phanerozic	Cenozoic	Quaternary		Holocene	11,000yrs-today
				Pleistocene	1.8mya* - 11,000
		Tertiary	Neogene	Pliocene	5.3 – 1.8mya
				Miocene	23.7 – 5.3mya
			Paleogene	Oligocene	36.6 – 23.7mya
				Eocene	57.8 – 36.6mya
				Paleocene	66.4 – 57.8mya
	Mesozoic	Cretaceous			144 – 66.4 mya
		Jurassic			208 – 144 mya
		Triassic			245 – 208 mya
		Permian			286 – 245 mya
		Carboniferous	Pennsylvanian		320 – 286 mya
			Mississippian		360 – 320 mya
		Devonian			408 – 360 mya
		Silurian			438 – 408 mya
		Ordovician			505 – 438 mya
		Cambrian			570 – 505 mya
Proterozoic		Grouped as Precambrian			2500 – 570 mya
Archean					3800 – 2500 mya
Hadean					4500 – 3800 mya

(mya = million years ago)
*The age of the beginning of the Pleistocene is in dispute

During the early Holocene (11 to 8 kya) the climate was transitional between that of the late Wisconsin and more modern regimes (Van Devender 1990). Variations in the Earth's orbital parameters over the Holocene influenced changes in the distribution of solar radiation on the planet's surface. These variations raised summer temperatures and intensified the summer monsoons as the summer solar radiation increased by 7% (Gates 1993, Kutzbach 1983, Van Devender 1990). The ice retreated and the winter jet stream no longer divided around it. The anticyclone over the ice weakened enough for the westerly winds to displace easterlies in the western United states. Lake levels began to drop in the western United States, probably because of high insolation (Gates 1993). Summer temperatures were still cooler, precipitation was greater, and summer rainfall was more dependable than today (Van Devender 1990).

By the mid Holocene (8 to 4 kya) the summer solar insolation was 8% higher than today, the climate had warmed, and the Laurentide ice sheet had retreated toward Hudson Bay (Gates 1993). The glacial anticyclone had weakened in eastern North America, and the Pacific anticyclone had strengthened, sending moist warm air off the Pacific Ocean and Gulf of Mexico into the southwestern and central United States (Gates 1993). Lake levels were lower than they were earlier, and these regions were warmer than today by 2° to 4°C. Meridional circulation transported maritime tropical air into the desert interior and increased summer rainfall (Gates 1993; Smith et al. 1997). However, the environmental conditions became more arid than the present from the northward displacement of the jet stream and failure of summer monsoons (Spaulding 1991, Moran and Morgan 1997).

In the Late Holocene summer temperatures were 2° to 4°C higher in both Europe and North America than they are today (Gates 1993). Summer insolation was stronger by 4% and winter insolation was reduced by 4%. This period is known as the post glacial climatic optimum (Gates 1993). By 4 kya the modern climatic regime became established. Reduction in the frequency of winter freezes and adequate summer rainfall combined to produce more subtropical climates in the Sonoran Desert as more frost sensitive elements of the flora migrated to their present northern ranges.

Changes in vegetation

Repeated wet and dry cycles associated with global, glacial-interglacial (pluvial) events during the Pleistocene caused cyclic expansion and contractions in the flora of the Sonoran Desert. The maximum development of Wisconsin period occurred between 24 and 17 kya, with pluvial conditions extending to ca. 9 kya in most areas. Under these climatic conditions, many of the internal drainage basins in the Basin and Range Province, including the Sonoran Desert were perennial lakes (Smith et al. 1997). This phenomenon caused desert plants to become restricted to xeric outcrops during the wetter, pluvial periods, and promoted hybridization and genetic mixing of formerly divergent biota. The evolving taxa were restricted during times of aridity, which accelerated the evolution of new desert taxa (Stebbins 1952, Smith et al. 1997). Pigmy conifer woodlands, including singleleaf piñon (*Pinus monophylla*), juniper (*Juniperus* spp.), scrub liveoak *(Quercus turbinella*), and Joshua-tree (*Yucca brevifolia*) were displaced 600 m to 1200 m downward in elevation into the regions now occupied by the Sonoran Desert (Clisby and Sears 1956, Martin 1963, Martin and Mehringer, 1965, Axelrod 1979, Van Devendar 1990, McClaran and Brady 1994, Smith et al. 1997).

Van Devender (1990) reported the Sonoran Desert vegetation sequence from the late Wisconsin glacial period through the Holocene culminating in the relatively modern communities was unidirectional. Overall the sequential changes were similar to moving down in elevation or south in latitude. There was a four-part vegetation sequence in the Arizona Upland subdivision (ca. 550 to 1550 m): a late Wisconsin woodland dominated by singleleaf piñon and juniper with shrub liveoak and or Joshua-trees; an early Holocene woodland with juniper and, in some cases scrub liveoak, with desert riparian trees and Sonoran desert shrub plants; a middle Holocene Sonoran desert scrub with brittle bush (*Encelia* spp), saguaro (*Carnegiea gigantea*), and riparian trees; and a late Holocene Sonoran desert scrub with more subtropical desert plants (Table 1.2). Below 600 m, the California juniper woodlands or Mojave desert shrub apparently changed little from the late Wisconsin into the early Holocene. The same can be said for lower Colorado River Valley desert shrub communities of the middle and late Holocene.

Stability of Sonoran Desert Plant Communities

Delcourt and Delcourt (1983) found that stable vegetation communities of full-glacial times were replaced by relatively unstable vegetation during late-glacial warming, and subsequent stable communities followed after 9 thousand years (kya). Accordingly, they proposed that plant communities have been in dynamic equilibrium in the Sonoran Desert region with relatively constant flora throughout the late Quaternary period (ca. 11 to 9 kya.). However, in his work with packrat middens, Van Devender (1990) found that Sonoran Desert plants attained their present ranges at different times, and community composition has not only changed during the last 11ky, but subsequently continued to vary during lesser climate episodes. This suggests differential responses of plant species to climate changes. Therefore, continual variation in climate at several scales has resulted in dynamic Sonoran Desert plant communities that rarely, if ever, reach equilibrium (Van Devender 1990).

Van Devender (1990) concluded that Sonoran Desert plant communities are loosely knit assemblages of individual species with different physiological tolerances to environmental factors and there has never been a unified Sonoran Desert community with a fixed assemblage of species (Betancourt et al. 1990). This is consistent with the ecological succession theories described by Shreve (1951) and Gleason (1939).

The Arizona Upland Subdivision

The Arizona Upland Subdivision of the Sonoran Desert was termed by Shreve (1951) as the crassicaulescent or stem succulent desert, because of the importance of cacti in the botanical communities. It is variously referred to as the Arizona Desert, Palo Verde Cacti Desert, and *Cercidium-Opuntia* Desert (Turner 1994). It includes some of the most famous and picturesque portions of the Sonoran Desert (Fig. 1.2) where the vegetative characterization includes the giant saguaro (*Carnegiea gigantea*) and associated small trees, such as foothill palo verde (*Cercidium microphyllum*). Over geologic time this vegetation represents a new vegetation type of cold-tolerant Sonoran Desert plants, which developed during the Holocene. Van Devender (1990)

described the migration of Sonoran Desert plants as moving from the mainland to the Baja peninsula during the Wisconsin period because of the winter rainfall. As chaparral and juniper woodland retreated to higher elevations during the Holocene, the desert shrub and succulent plants expanded north (Van Devender 1990).

Human Population Changes

The warm, dry winter climate and unique, picturesque vegetation in this subdivision has long attracted people to live within south central Arizona. National and international visitors are also attracted to the region during the winter season. Marshall et al. (2000) reported population in the Sonoran Desert Ecoregion in 1970 totaled ca. 3.5 million and increased to 6.9 million in 1990. The average human population growth reached 4.1% during the 1970's slowing only slightly to 3.3% during the 1980's and 3.2% during the first half of the 1990s. For comparison, the average annual population growth for the entire U.S. is 0.8%, and 1.6% for Mexico (Marshall et al. 2000). At a growth rate of 3.2%, a population doubles approximately every 22 years. Rapid, sustained population growth is anticipated to continue through at least the next two decades on both sides of the US/Mexico border with the total population nearing 12 million by 2020 (Marshall 2000). The population growth rate in the Phoenix Metropolitan Area was among the fastest in the country since the early 1980's, increasing from 331,770 in 1950 to 2,806,100 in 1998 (Arizona Population Statistics Unit 1999). The rapid growth has driven new home construction and subsequent urban sprawl into the Sonoran Desert. According to Johnson (1997), the Phoenix Metropolitan Area was developed at a rate of one acre per hour (24 hour period) during 1986 through 1992.

Table 1.2. Vegetation development over the past 20,000 years in the Sonoran Desert (Van Devender 1990, Smith et al. 1997).

Time Period		Dominant vegetation Type
Late Wisconsin	(21– 11 kya)	*Pinus – Juniperus – Quercus* woodland
Early Holocene	(11 – 8 kya)	*Juniperus – Quercus* woodland/Desert shrubs
Middle Holocene	(8 – 4 kya)	*Acacia – Prosopis – Cercidium* woodland
Late Holocene	(< 4 kya)	*Larrea – Cercidium – Carnegiea* desert scrub

Kya = thousand years ago

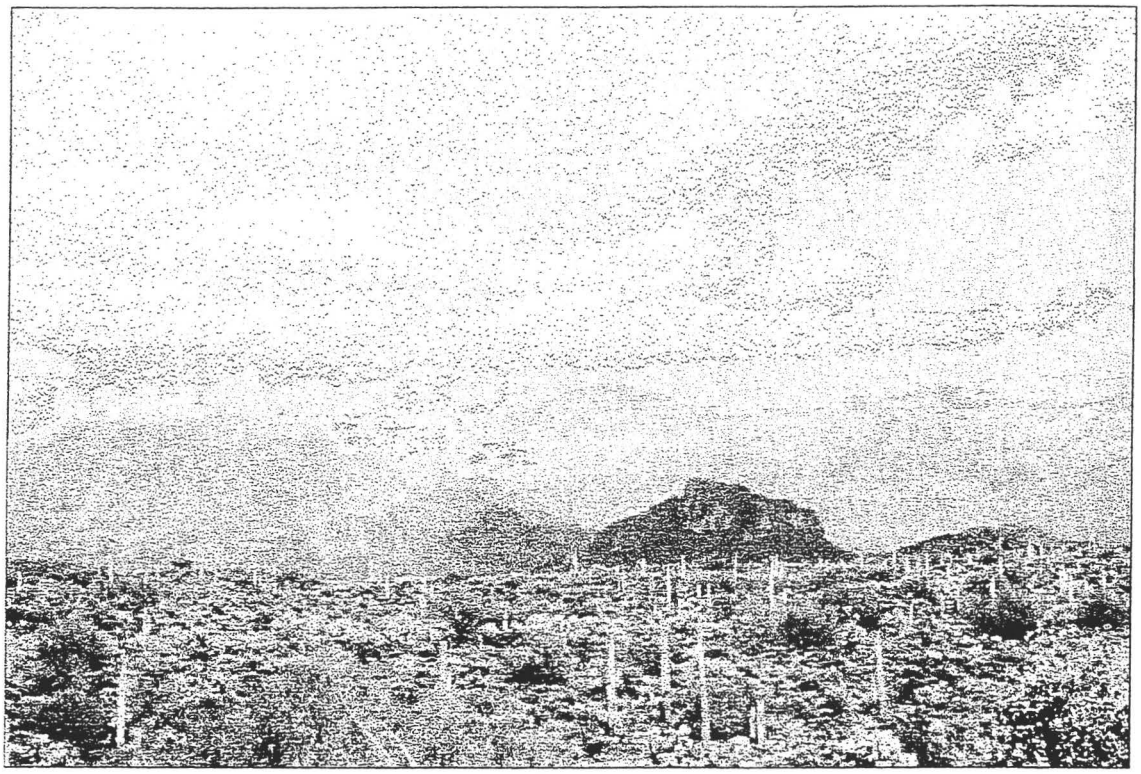


Fig. 1.2. View of the Arizona Upland Subdivision of the Sonoran Desert North of Mesa, Arizona, on the Tonto National Forest.

Concomitant with the increase in human population is an increase in anthropogenetic impacts on the Sonoran Desert, and increased concern for continued existence of native flora. Several factors potentially cause changes in the floristic characteristics in the Sonoran Desert. These factors include the invasion of exotic plants (especially grasses), improper grazing of domestic and wild herbivores, damaging vegetation by all-terrain recreation vehicles, removal of native plants for landscaping, and fire ignition by vehicles along highways (McLaughlin and Bowers 1982, Cave and Patten 1984, Rogers 1986, Hanley and Brady 1988, Abou-Haidar 1989, Narog et al. 1996, Wilson et al 1995). These factors, individually and interactively, affect the biotic communities in the Sonoran Desert.

CHAPTER 2

CLIMATIC AND ANTHROPOGENIC INFLUENCES ON SONORAN DESERT FIRE REGIMES

Introduction

Native Sonoran Desert plants lack fire-adapted characteristics, and their discontinuous spacing indicate that recurring fires were not significant in the long-term ecological history of the Sonoran Desert (Rogers 1986, Smith et al. 1997). However, the fire regime in the Arizona Upland Subdivision of the Sonoran Desert has been an increasing concern during the past three decades. Increased fire occurrence could alter Sonoran Desert vegetation by removing several species, including the indigenous saguaro (*Carnegiea gigantea*) from plant communities (Rogers and Steele 1980, Cave and Patten 1984, Rogers 1985, Smith et al. 1997, Wilson et al. 2000).

The spatial and temporal variation of fire in the Sonoran Desert appears to be highly sensitive to changes in climatic and anthropogenic activities. Climate and human activities influence fire regimes through their effects on fuel condition and fire ignition (DeBano et al. 1998, Veblen et al. 2000). Precipitation and temperature govern the amount of vegetation that is produced and the moisture content of the fuels. Human activities often provide an ignition source to the fuels.

Effects of Anthropogenic Activities

The warm dry winter climate and unique, picturesque vegetation of the Sonoran Desert are some of the factors that have attracted rapid human population growth in central Arizona during the past two decades. The population growth rate in the Phoenix metropolitan area has been among the fastest in the country since the early 1980's. The population of Maricopa County (including the Phoenix Metropolitan Area) increased from 331,770 in 1950 to 3,072,149 in 2000 (Arizona Population Statistics Unit 2001). The influx of people, and a healthy employment economy, has created a demand for new home construction and consequently, urban sprawl into the Sonoran Desert. Between 1986 and 1992 undeveloped areas in the Phoenix metropolitan were cleared and developed at a rate of two and one-half hectares per hour over a 24-hour period (Johnson 1997). Concomitant with the increase in population of Maricopa County is an

increase in anthropogenic activities including off-highway vehicles (OHVs), camping, and target shooting in the Sonoran Desert of the Tonto National Forest (TNF). From 1990 to 1997 the annual recreation visitor days (RVDs) increased from approximately 7 million to 13 million on the Tonto National Forest (Killebrew, personal communication 2000). These anthropogenic activities have been a source for fire ignition in the predominately annual vegetation, growing adjacent to the highway shoulders (Figs. 2.1 and 2.2). Consequently, fire has impacted the native vegetation and eliminated many native desert perennials over large tracts adjacent to major roads (McLaughlin and Bowers 1982, Cave and Patten 1984, Rogers 1986, Abou-Haidar 1989, Wilson et al. 1995, Narog 1996).

Climatic Effects

A bimodal rainfall regime occurs in the Sonoran Desert, and produces both a spring and summer growing season. Consequently two floristically distinct groups of plants grow and vary with the amount of precipitation (Shreve and Mallery 1964, Rogers and Vint 1987, McClaran and Brady 1994). Rogers and Vint (1987) evaluated historical fire and climate records from the Sonoran Desert and concluded that more hectares were burned after two consecutive wetter than normal winters. Furthermore, linkages have been identified between the occurrence of Sonoran Desert fires and the production of herbaceous vegetation (Humphrey 1974, 1981, Rogers and Steel 1980, Cave 1982, McLaughlin and Bowers 1982, Goldberg and Turner 1986, Rogers and Vint 1987, Steenbergh and Lowe 1983, Venable and Pake 1999). Fires generally occur in the Sonoran Desert after winter precipitation produces a crop of exotic and native annual vegetation. This herbaceous vegetation cures with the dry hot conditions during the late spring and forms dense stands of fine fuel that extends from shoulders of the highways into the native plant communities. The highways often provide an ignition source from sparks created by vehicles and fire often spreads from the roads into the Sonoran Desert (Figs. 3 and 4).

In order to predict fire hazard and evaluate the effects of suppression actions, the linkage between climatic variations needs to be identified. Swetnam and Betancourt (1998) identified the

relationship between the tropical Pacific sea surface temperature and pressure known as the Southern Oscillation, with the occurrence of fires in forested ecosystems in the Southwest. The warming of sea-surface temperatures in the equatorial region of the Pacific Ocean between South America and the date line is known as the *El Niño* phase of the Southern Oscillation, and the reverse phase, related to ocean cooling, is termed *La Niña. El Niño*/Southern Oscillation (ENSO) refers to the coupled ocean-atmosphere system in which *El Niño* and *La Niña* are extreme phases of oscillation (Veblen et al. 2000). Tree-ring studies and documentary records of fire history in the Southwest show that fires are more widespread during La Niña events in most ecosystems in the Southwest (Swetnam and Betancourt 1998, Veblen et al. 2000). However, the reverse is true in the Sonoran Desert. With *El Niño*, the period from October thought March tends to be wetter than usual the year after the onset of *El Niño*, and below average after the onset of *La Niña* (Redmond 1999, Veblen et al. 2000).

It is important to understand the influence in anthropogenic and climatic factors on the number of fires and hectares burned, in order to make important fire management decisions in the Sonoran Desert ecosystem. Although factors that generally influence fire in the Sonoran Desert have been identified, more work is needed to scientifically test their influence on the number of fires and hectares burned. Recent work has been completed on the TNF (Wilson et al. 1995, Narog 1996) however, this work concentrates on the effects of fire on Sonoran Desert vegetation and not the influence of climatic and anthropogenic factors on fire regimes. Studies in the mid-80s identified climatic effects on number of hectares burned in the Sonoran Desert on the TNF (Cave 1982, Rogers 1985, 1986, 1987, Rogers and Vint 1987, Sweat 1995). Rogers (19 86) studied the number of fires and area burned on the Tonto National Forest for a 29 year period (19 55 - 1983). He determined that the number of fires increased in the Sonoran Desert whereas the number of hectares burned did not. Seventeen years of additional data has been collected since 1983 and there is a need to conduct additional studies to gain a solid understanding of the relationship between climatic and anthropogenic factors and the fire regime in the Sonoran Desert. The objective of this study is to determine which anthropogenic and climatic factors

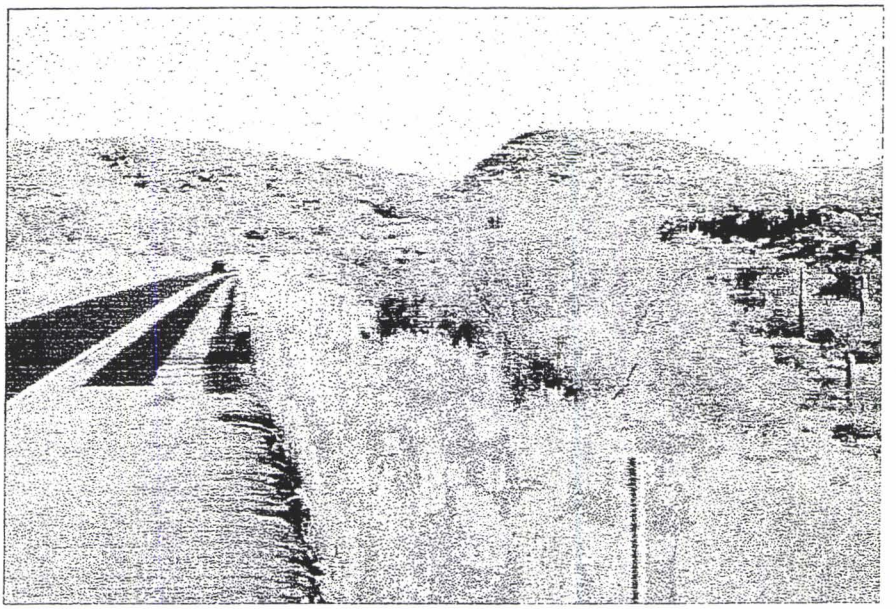


Fig. 2.1. During winters when precipitation is high, annual exotic grasses grow next to the road shoulder along SH 60 east of Apache Junction, Arizona. The grass provides a consistent source of flammable material, which can be ignited by sparks from vehicles or cigarette ashes.

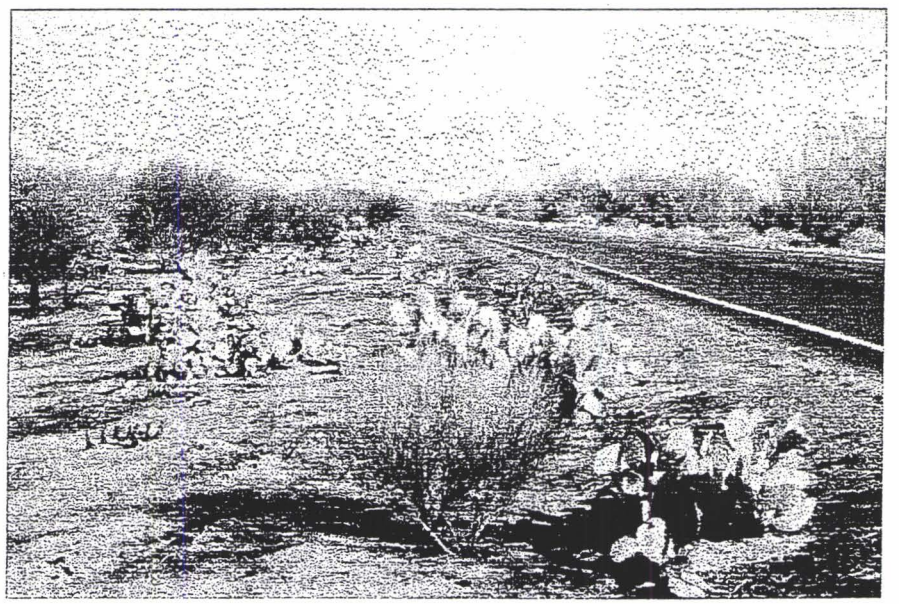


Fig. 2.2. Burned vegetation in the Sonoran Desert along State Highway 60 east of Apache Junction, Arizona. Fires along the highway rapidly spread into the adjacent native Sonoran Desert.

significantly influence the number of fires and number of hectares burned annually in the Sonoran Desert ecosystem. The variables evaluated for their effect on numbers of fires and hectares burned are: precipitation, annual traffic on Highways 60 and 87, and human population in Maricopa County.

Methods

Study area

The study area consists of the Sonoran Desert ecosystem on the Tonto National Forest (TNF) in central Arizona (Fig. 2.3). The Sonoran Desert occupies 364,225 hectares (USGS 2000, GES 2000) in the southern one-third of the forest. It ranges from the southern forest boundary to ca. 34^0 N latitude. It is found in the elevation range of ca. 427 meters to 1067 meters on the TNF. It generally extends from Phoenix north to Sunflower, and from the east side of Roosevelt Lake to Interstate Highway 17 on the west. Temperatures range from ca. 0 to 21^0 C during the winter and 21^0 to 43^0 C during the summer. Mean annual precipitation, during the past 45 years was 368 ± 19 mm of which 34% fell during winter (December-February), 18% during the spring (March, April and May) 22% during the summer (June-August), 26% during the fall. The study area is typical of the Arizona Upland Subdivision (Shreve 1951), characterized by: saguaro, foothill palo verde (*Cercidium microphyllum*), creosote bush (*Larrea tridentada*), catclaw acacia (*Acacia greggii*), white thorn acacia (*Acacia Constricta*), mesquite (*Prosopis* spp.), bursage (*Ambrosia deltoidea*) and brittle bush (*Encelia farinosa*).

The Phoenix Metropolitan Area delimits the southern boundary of the Tonto National Forest. Its sprawling boundaries extend ca. 110 km from southeast to northwest. The metropolitan area is located entirely in the Sonoran Desert, however, the northern and eastern boundaries generally intersect the Arizona Upland Subdivision vegetation.

Data Collection

Data describing individual fires in Sonoran Desert on the TNF were extracted from the Forest's individual fire reports. The reports describe the location, date, size, cause, elevation and

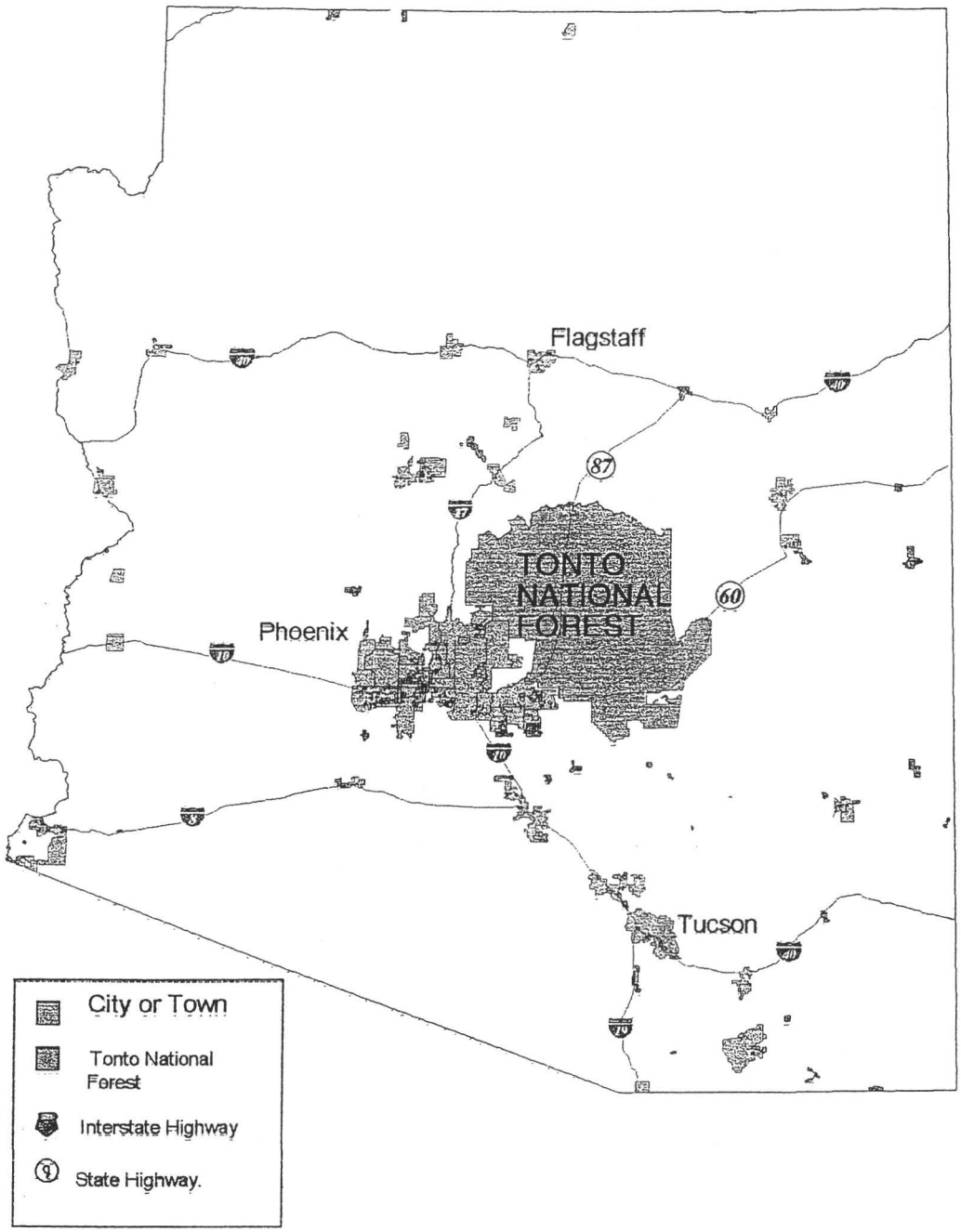


Fig. 2.3. Map of Arizona showing the administrative boundary of the Tonto National Forest

fuel type. Data were entered into Arch View GIS (graphical information system) and formatted similarly to the work presented by Swantek et al. (1999). The GIS maps show the fire ignition location of small fires, and the boundary of fires that were 2.9 hectares in size or larger. Monthly precipitation totals from 1953 through 2000 were extracted from the National Oceanic Atmospheric Administration (NOAA) Climate Data Center records. The monthly totals from the Bartlett Lake, Stewart Mountain and Roosevelt Lake weather stations were averaged to represent the Sonoran Desert moisture regime on the TNF. Precipitation variables were separated into sub-categories as described in Table 2.1.

El Niño Southern Oscillation (ENSO) tables and graphs which stratified the June through November Southern Oscillation Index (SOI) for Phoenix, Arizona, were used to compare *El Niño* and *La Niña* years with numbers of fires and hectares burned on the Tonto National Forest.

The anthropogenic factors evaluated were: The "population of Maricopa County", and the "vehicular traffic" on State Highway 87 (SH 87) and State Highway 60 (SH 60) from 1955 through 2000 (Table 2.1). The population records of Maricopa County were obtained from the Census Bureau, and the traffic data were obtained from the Arizona Department of Transportation (ADOT). Traffic data came from vehicle count meters located on SH 87 at the Bush Highway intersection about 24 km north of Fountain Hills, Arizona, and on SH 60 at the Florence Junction intersection 27 km east of Apache Junction, Arizona. The annual mean twenty-four hour vehicle traffic data is the sum of both highways.

Statistical Analysis

All statistical analyses were conducted with the Statistical Package for Social Sciences (SPSS Base 10.0)* software. Scatter plot matrices and histograms were plotted to test normality of data and the effect of logarithmic transformations were tested. Analysis of variance (ANOVA) was used to evaluate the significance of the regression coefficients at $P = < 0.05$. Because of the

* This software is not endorsed by Arizona State University

Table 2.1. Variables analyzed for their effect on occurrence and size of fires in the Sonoran Desert.

Variables:	Description
Time	Years from 1955 through 2000. (Numbers of fires and hectares burned were recorded annually)
Population	Annual Human Population in Maricopa County
Traffic	24 hour vehicle traffic using SH 87 (at Bush Highway) and SH 60 (at Florence Junction) on the TNF (ADOT 2000)
Number of Fires	Total number of fires detected in the Sonoran Desert during the calendar year.
Hectares Burned	Total number hectares burned annually in the Sonoran Desert on the TNF
Annual precipitation	Total calendar year precipitation (NOAA 2000)
Winter precipitation	Precipitation during the contiguous months of December, January and February
Spring precipitation	Precipitation during the contiguous months of March, April, and May
Summer precipitation	Precipitation during the months of June, July and August
Fall precipitation	Precipitation during the contiguous months of September, October, and November
Summer and winter precipitation	Precipitation during the previous summer and current winter
Two consecutive winters precipitation	Precipitation during the previous winter year plus the current winter
Three consecutive winters precipitation	Precipitation during previous two winters plus the current winter
Consecutive winter, summer and winter precipitation	Previous winter plus previous summer plus current winter precipitation.

high variability in climatic data the 0.05 probability level was used rather than a more stringent probability level (P = 0.01). It is estimated that a higher risk of a type II error could result with the 0.01 probability level, than the risk of a type I error with the 0.05 probability level.

Multiple regression analyses were used to determine the effect of variables on the number of fires and number of hectares burned. Stepwise regression analysis was used to assess the ability of the independent variables to predict the number fires and hectares burned in the Sonoran desert. The "forward selection" regression analysis procedure was used to find the best-fit polynomial model to the data. Subsequent to fitting the linear regression model ($Y_i = \alpha + \beta X_{i)}$, succeeding polynomial equations (quadratic, cubic) were applied until the "t" test failed to reject the null hypothesis indicating the previous regression model best described the dependence of number of fires and hectares burned on the independent variables.

Results

Anthropogenic Effects

The human population of Maricopa County increased from 509,650 to 3,072,149 during the study period (1955–2000), and traffic along SH 87 and SH 60 increased from 3,259 to 19,235 vehicles day^{-1} (Table 2.2, Appendix C). Seventy-five percent of the fires in the Sonoran Desert were person caused, and twenty-five were lightning caused. The majority of the Sonoran Desert fires occurred in May (26.9%) and June (25.2%) during the study period (Table 2.3). This is usually before the summer monsoon and lightning season occurs.

The annual number of fires appears to have increased sharply from 1955 through the early 1980's and stabilized somewhat from 1990 through 2000 (Fig. 2.4); however, the percentage of person caused fires has not significantly (P = < 0.05) changed during the past 45 years (Fig. 2.4). The relationship between both human population and traffic, and the number of fires in the Sonoran Desert, was significant (P = < 0.05) ; however, these factors were not significantly (P = <0.05) related to the number of hectares burned. A cubic curve best fits the relationship between

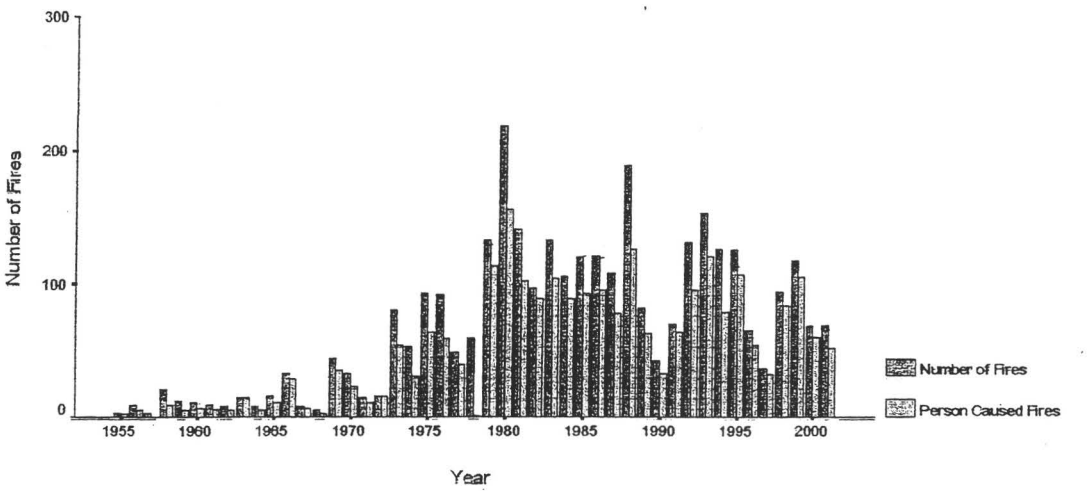


Fig. 2.4. Total fires and person caused fires in the Sonoran Desert on the Tonto National Forest from 1955-2000.

Table 2.2. Summary of anthropogenic factors and fire occurrence by decade.

Decade	Mean annual 24 hour highway traffic on SH60 + SH87	Mean annual number of fires detected	Mean annual area burned (hectares)
1950-59	3259	9.6	4221
1960-69	4867	15.7	144
1970-79	8858	62.3	21348
1980-89	10560	31.5	1606
1990-99	15089	96.1	1095
2000	19235	68	38.4

the number of fires and population ($y = - 98.225 + 34x - 2.0^{E-6}x^2 - 2.5^{E-11}x^3$) and traffic ($y = -0.420 + .0002x - 2.6^{E-12}x^2 - 1^{E-17}x^3$), (Table 2.4, Fig. 2.5b and c). Fig. 2.5b and c show a rapid rate of increase in number of fires as population and traffic increased, however this rate is reduced as the traffic and population continue to increase. This change in the rate of increase could be a result of improved road design (widening), reducing the amount of sparks that reach the roadside vegetation, and improved regulation of camping in heavy concentration areas over time.

Climatic Effects

There was a significant relationship ($P = 0.05$) between numbers of fires and: total annual precipitation (Fig. 2.5d), winter precipitation (Fig. 2.5f), two consecutive winters precipitation (Fig. 2.5h), three consecutive winters precipitation (Fig. 2.5i), consecutive winter, summer and winter precipitation (Fig. 2.5j), spring precipitation (Fig. 2.5k), consecutive winter and spring precipitation (Fig. 2.5m, Table 2.4). These seasons and combinations of seasons of precipitation All contribute to the growth of winter and spring ephemeral plants (Shreve and Mallery 1964, Rogers and Vint 1987, McClaran and Brady 1994), which could provide a source of fuel for fires in the Sonoran Desert. Summer precipitation, fall precipitation, and consecutive summer and winter precipitation did not have a significant relationship to the number of fires (Figs. 2.5e, g and l). Summer precipitation appears to have an inverse relationship on the number of fires, but the relationship was not significant. In the Sonoran Desert fire regime, summer precipitation usually occurs during the months June, July and August, which is during or following the most active fire months. Therefore, summer precipitation with higher humidity during the monsoon season would be expected result in a decrease in the number of fires and number of hectares burned.

The number of hectares burned increased with an increase in two and three consecutive winters'; consecutive winter and spring; and consecutive winter, summer and winter precipitation (Fig. 2.5j). The number of hectares burned between 1955 and 1999 appeared to respond to the *El Niño*/*La Niña* patterns. The number of fires, and hectares burned, show a positive relationship with preceding year SOI. The strong *El Niño* lag years often supported a higher number of

Table 2.3. The mean monthly percentage of fires that occurred from 1951 through 1999 in the Sonoran Desert of the Tonto National Forest.

Month	Percentage of Fires	Month	Percentage of Fires
January	0.4	February	0.3
March	1.9	April	6.2
May	26.9	June	25.2
July	21.6	August	8.8
September	5.3	October	1.8
November	1.5	December	0.1

Table 2.4. Regression coefficients and "F" values for the relationship between each independent variable and number of fires and hectares burned. Quadratic and cubic curves are also presented.

Dependent	Method	R^2	df	F	Sig.	b_0	b_1	b_2	b_3
				Population					
Fires	Linear	.381	44	27.05	.000	-.6655	4.7E-05		
Fires	Quadratic	.622	43	35.45	.000	-123.50	.0002	-6.0E-11	
Fires	Cubic	.626	42	23.40	.000	-90.420	.0002	2.6E-12	-1E-17
Hectares Burned	Linear	.005	44	.22	.640	761.245	.0003		
Hectares Burned	Quadratic	.061	43	1.39	.261	-2285.7	.0049	-1.0E-.09	
Hectares Burned	Cubic	.062	42	.92	.439	-3305.8	.0072	-3.0E-.09	3.0E-16
				Traffic					
Fires	Linear	.389	44	28.01	.000	-2.0504	.0075		
Fires	Quadratic	.508	43	22.18	.000	-77.723	.0263	-9.0E-.07	
Fires	Cubic	.510	42	14.55	.000	-98.255	.0341	-2.0E-.06	2.5E-11
Hectares Burned	Linear	.000	44	.02	.901	1064.33	.0117		
Hectares Burned	Quadratic	.033	43	.73	.489	-979.82	.5197	-3.0E-.05	
Hectares Burned	Cubic	.052	42	.76	.521	-4424.4	1.8308	-.0003	4.2E-09
				Total Annual Precipitation					
Fires	Linear	.123	44	6.19	.017	14.7590	.1472		
Fires	Quadratic	.158	44	4.04	.025	-59.621	.5224	.0004	
Fires	Cubic	.161	42	2.68	.059	-13.146	.1558	.0005	-6.E-07
Hectares Burned	Linear	.004	44	.17	.681	677.357	1.3526		
Hectares Burned	Quadratic	.044	43	.98	.382	-3437.5	22.1055	-.0231	1.5E-05
Hectares Burned	Cubic	.044	42	.65	.589	-4527.7	30.7050	-.0437	
				Summer Precipitation					
Fires	Linear	.000	44	.01	.915	67.3349	.0198		
Fires	Quadratic	.036	44	.80	.80	32.4651	.8014	-0034	
Fires	Cubic	.038	42	.56	.56	50.1073	.2086	-0021	-1.E-05
Hectares Burned	Linear	.024	44	1.08	.304	1981.52	-9.8508		
Hectares Burned	Quadratic	.025	43	.55	.579	2299.47	-16.978	-0306	
Hectares Burned	Cubic	.026	42	.38	.768	1619.24	5.8783	-.1779	.0005
				Winter Precipitation					
Fires	Linear	.086	44	4.15	.048	44.4514	.1939		
Fires	Quadratic	.086	43	2.03	.144	42.4869	.2255	-9.E-05	
Fires	Cubic	.105	42	1.65	.193	71.2589	-.6180	.0060	-1.E-05
Hectares Burned	Linear	.046	44	2.14	.151	244.246	7.3659		
Hectares Burned	Quadratic	.074	43	1.72	.191	-949.08	28.5341	-.0538	
Hectares Burned	Cubic	.085	42	1.30	.286	178.929	-6.5345	.1833	-.0004
				Consecutive Summer and Winter Precipitation					
Fires	Linear	.052	44	2.42	.127	41.3322	.1329		
Fires	Quadratic	.055	43	1.26	.295	53.6236	.0213	.0002	
Fires	Cubic	.055	42	.82	.491	58.7422	.0528	.0005	4. E-07
Hectares Burned	Linear	.025	44	1.11	.298	193.770	4.7197		
Hectares Burned	Quadratic	.048	43	1.07	.351	-1573.5	20.7556	.0301	
Hectares Burned	Cubic	.053	42	.78	.510	314.675	-6.5985	.0814	-.0001
				Two Consecutive Winters Precipitation					
Fires	Linear	.262	44	15.64	.000	9.9382	.2320		
Fires	Quadratic	.263	43	7.67	.001	15.9641	.1844	7.7E-05	
Fires	Cubic	.268	42	5.13	.004	37.9336	-.1153	.0012	-1. E-06
Hectares Burned	Linear	.183	44	9.86	.003	-1376.5	10.0319		
Hectares Burned	Quadratic	.194	43	5.86	.010	-148.64	.3305	.0156	
Hectares Burned	Cubic	.211	42	3.74	.018	1935.81	-28.108	.1236	-.0001
				Three Consecutive Winters Precipitation					
Fires	Linear	.367	44	25.51	.000	-12.982	.2136		
Fires	Quadratic	.372	43	12.71	.000	10.9095	.0932	.0001	
Fires	Cubic	.387	42	8.82	.000	-97.607	.9391	-.0018	1.4E-06
Hectares Burned	Linear	.249	44	14.57	.000	-2316.1	9.1008		
Hectares Burned	Quadratic	.303	43	9.35	.000	1942.61	-12.362	.0232	
Hectares Burned	Cubic	.304	42	6.12	.001	3617.33	-25.416	.0537	-2.E-05

(Table 2.4 cont.)

Dependent	Method	R^2	df	F	Sig.	b_0	b_1	b_2	b_3
----------Consecutive Winter, Summer and Winter Precipitation----------									
Fires	Linear	.236	44	13.59	.001	-4.4465	.2064		
Fires	Quadratic	.245	43	6.97	.002	30.3926	.0202	.0002	
Fires	Cubic	.256	42	4.81	.006	94.8123	-.6012	.0020	-2.E-06
Hectares Burned	Linear	.121	44	6.05	.018	-1394.8	7.6437		
Hectares Burned	Quadratic	.122	43	2.99	.061	-787.19	3.9735	.0048	
Hectares Burned	Cubic	.163	42	2.72	.056	5680.79	-58.410	.1827	-.0003
----------Spring Precipitation----------									
Fires	Linear	.187	44	10.09	.003	37.2804	.4835		
Fires	Quadratic	.272	43	8.05	.001	11.7407	1.3534	-.0047	
Fires	Cubic	.303	42	6.07	.002	-5.8851	2.5327	-.0203	5.1E-05
Hectares Burned	Linear	.041	44	1.90	.175	403.574	11.7765		
Hectares Burned	Quadratic	.070	43	1.61	.212	-353.85	37.5753	-.1396	
Hectares Burned	Cubic	.110	42	1.73	.175	704.767	-33.251	.7976	-.0030
----------Fall Precipitation----------									
Fires	Linear	.000	44	.0014	.970	68.3529	.0064		
Fires	Quadratic	.004	43	.09	.914	78.9749	-.2260	.0010	
Fires	Cubic	.068	42	1.02	.395	142.070	-2.5948	.0240	-6.E-05
Hectares Burned	Linear	.067	44	3.16	.082	2596.31	-15.124		
Hectares Burned	Quadratic	.108	43	2.60	.086	4321.95	-52.891	.1631	
Hectares Burned	Cubic	.128	42	2.05	.122	6154.68	-121.70	.8317	-.0018
----------Consecutive Winter and Spring Precipitation----------									
Fires	Linear	.160	44	8.41	.006	31.8638	.1933		
Fires	Quadratic	.225	43	6.23	.004	-12.193	.6388	-.0008	
Fires	Cubic	.245	42	4.54	.008	29.5810	-.0361	.0021	-3.E-06
Hectares Burned	Linear	.060	44	2.81	.101	1.1650	6.1178		
Hectares Burned	Quadratic	.133	43	3.29	.047	-2421.7	30.6188	-.0459	
Hectares Burned	Cubic	.167	42	2.80	.051	401.411	-14.996	.1506	-.0002
----------Time----------									
Fires	Linear	.462	44	37.79	.000	3.1014	2.8023		
Fires	Quadratic	.552	43	26.46	.000	-36.022	7.6928	-.1041	
Fires	Cubic	.645	42	25.41	.000	14.3018	-4.5049	.5378	-.0091
Hectares Burned	Linear	.011	44	.49	.489	650.490	22.3237		
Hectares Burned	Quadratic	.049	43	1.12	.337	-673.55	187.828	-3.5214	
Hectares Burned	Cubic	.064	42	.95	.423	355.131	-61.506	9.5995	-.1861

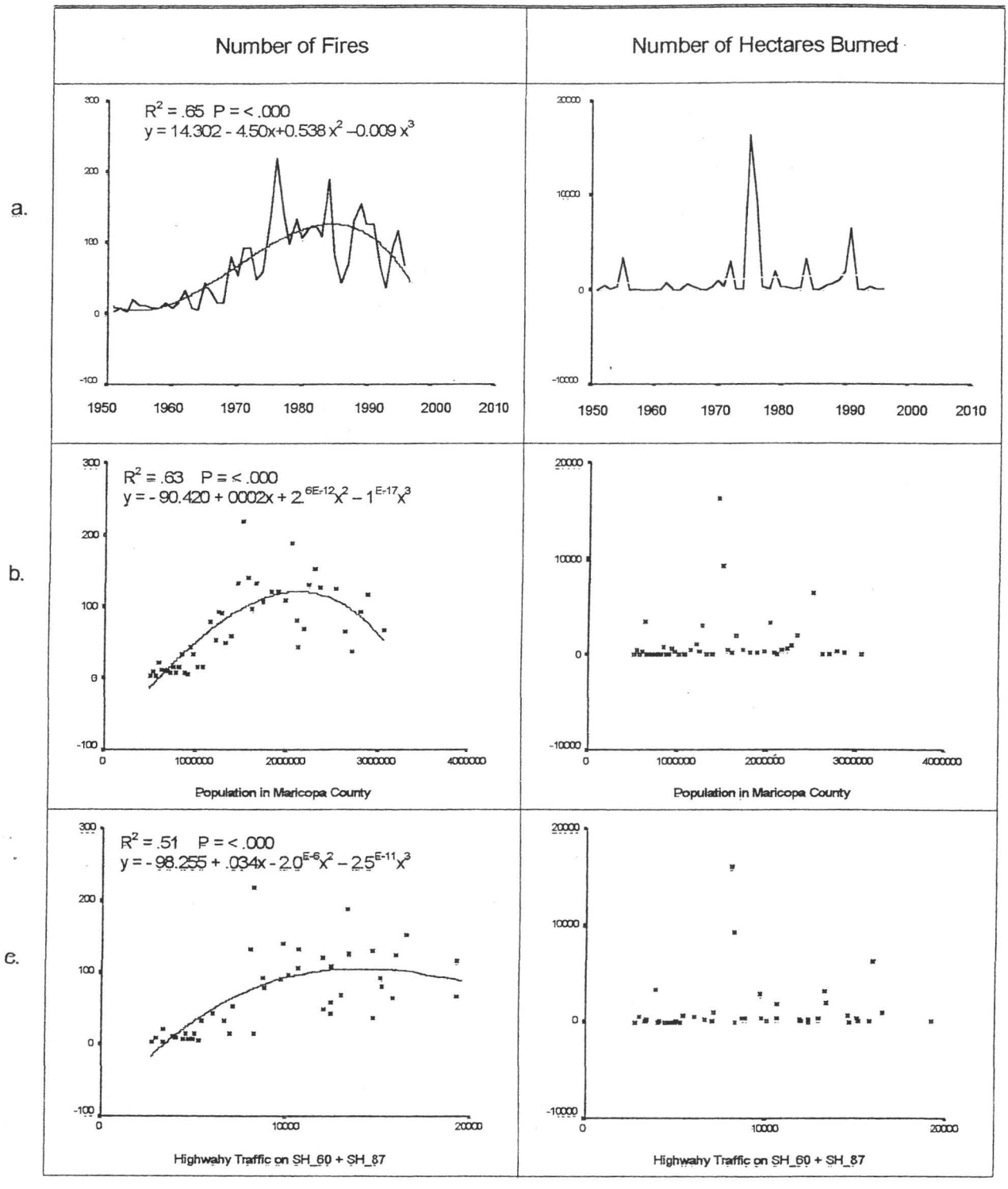

Number of Fires
Number of Hectares Burned
a.
R^2 = .65 P = < .000
y = 14.302 - 4.50x+0.538 x^2 –0.009 x^3
b.
R^2 = .63 P = < .000
y = - 90.420 + 0002x + 2.$^{6E-12}x^2$ – 1.$^{E-17}x^3$
Population in Maricopa County
c.
R^2 = .51 P = < .000
y = - 98.255 + .034x - 2.0$^{E-6}x^2$ – 2.5$^{E-11}x^3$
Highwahy Traffic on SH_60 + SH_87

Fig. 2.5. Relationship of climate and anthropogenetic variables on the number of fires and number of hectares burned in the Sonoran Desert. The "best fit" curve is (is not) shown for variables which have (do not have) a significant (P=< 0.01) relationship with numbers of fires and hectares burned.

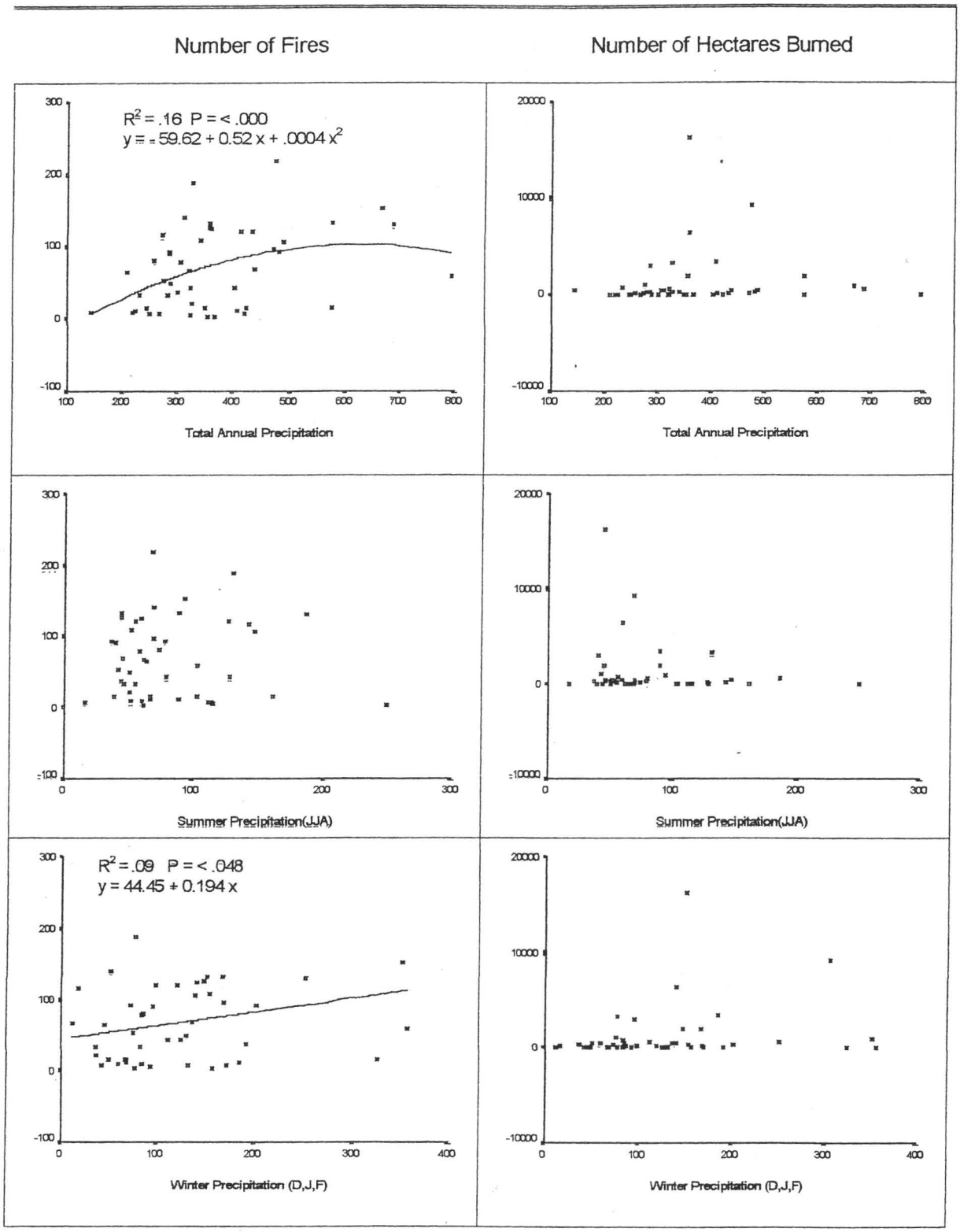
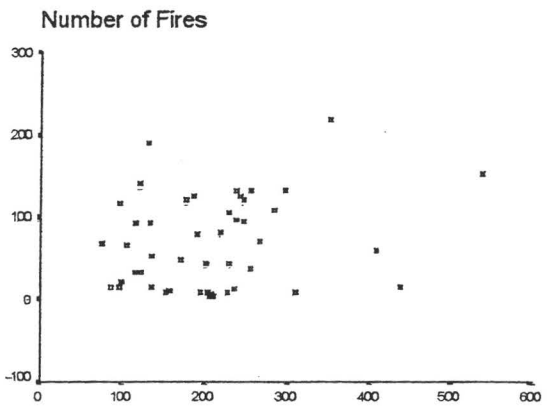
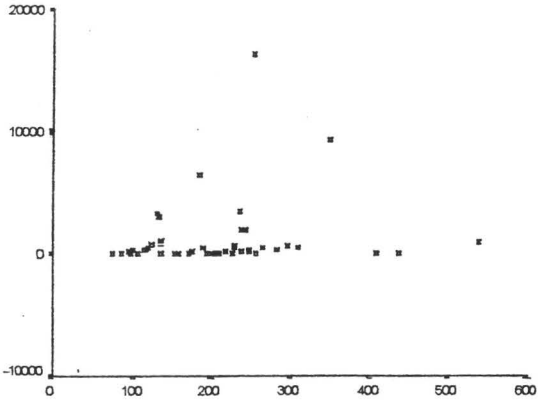
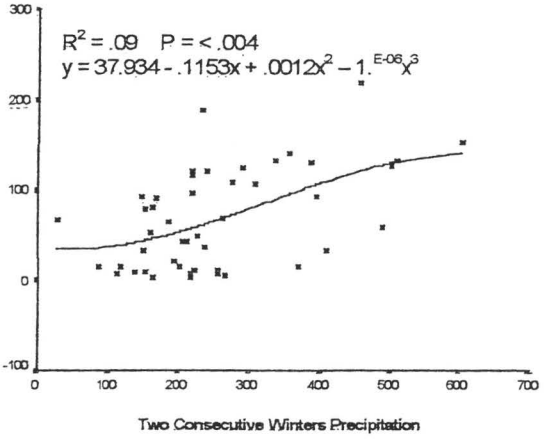
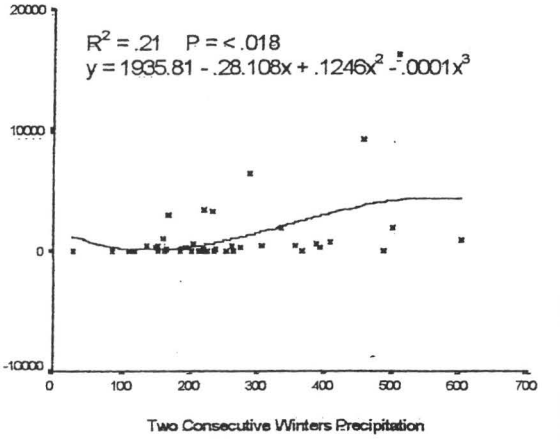
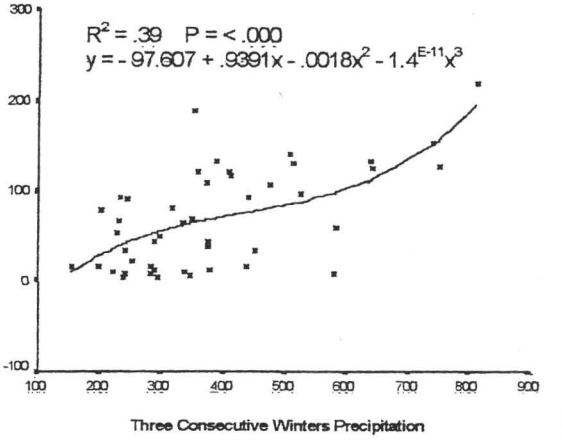
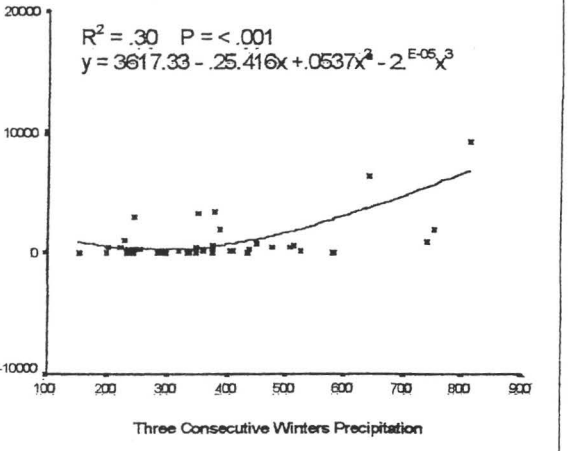


Fig. 2.5. Continued.

	Number of Fires	Number of Hectares Burned
g.		
h.		
i.		

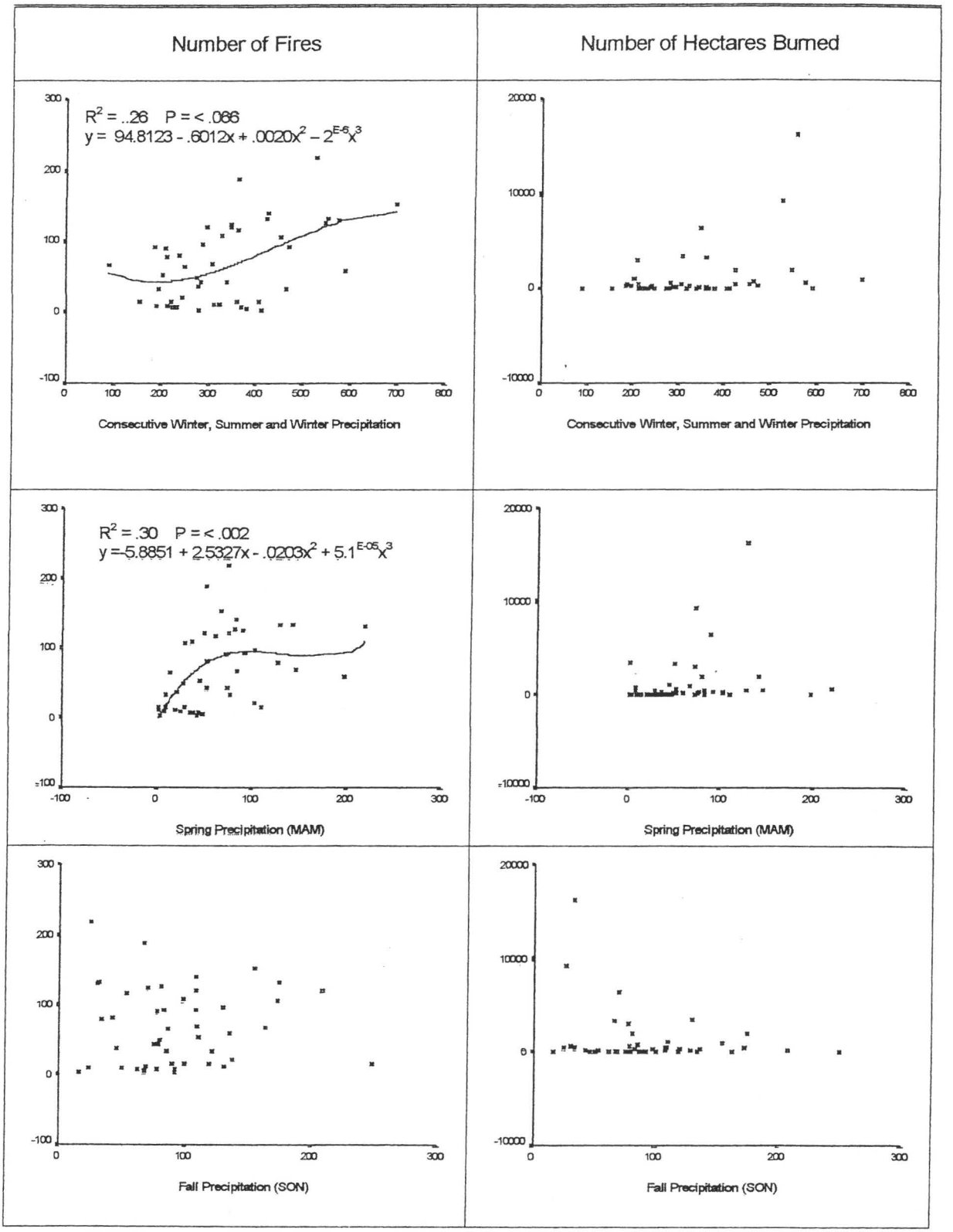

Number of Fires
Number of Hectares Burned
j.
R^2 = ..26 P = < .086
y = 94.8123 - .6012x + .0020x^2 – $2^{E-5}x^3$
Consecutive Winter, Summer and Winter Precipitation
Consecutive Winter, Summer and Winter Precipitation
k.
R^2 = .30 P = < .002
y = -5.8851 + 2.5327x - .0203x^2 + $5.1^{E-05}x^3$
Spring Precipitation (MAM)
Spring Precipitation (MAM)
l.
Fall Precipitation (SON)
Fall Precipitation (SON)

Fig. 2.5. Continued.

m.

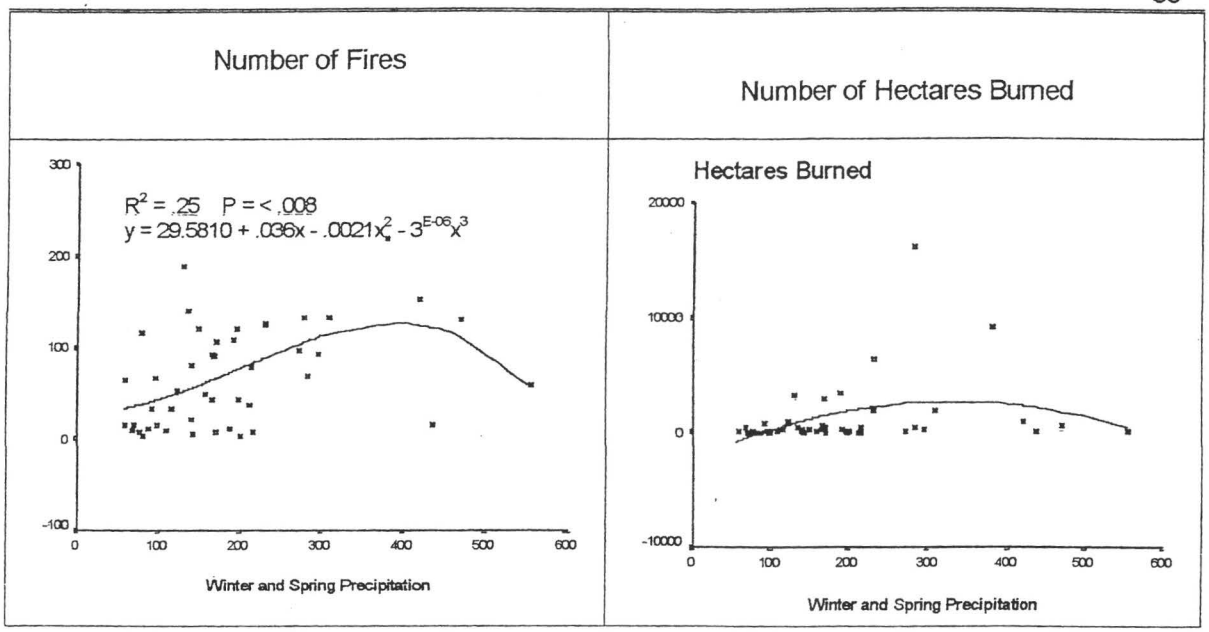


Fig. 2.5. Continued.

hectares burned and number of fires. Strong *El Niño* years occurred in 1965, 1972, 1977, 1982, 1987, 1993, 1994 and 1997. An increase in lag year hectares burned occurred in seven of the eight stronger *El Niño* years, and number of fires increased in six of the eight *El Niño* lag years (Table 2.5). Two strong and one moderate *El Niño* years occurred during the 1970s, which appeared to cause an increase in the number of hectares burned (Table 2.6). Although more hectares were burned during some decades it is difficult to determine a decadal pattern since the *El Niño—La Niña* events often occur more than once in a decade.

The most effective variables for predicting the number of fires based on the stepwise regression analysis were "traffic" and "three consecutive winters' precipitation" (Table 2.7). The stepwise regression analysis provides a significant (P= < .0001) regression coefficient (.0087, Table 2.7) for traffic as a single independent variable in the first model (R^2 = .44). Traffic and two previous winters precipitation together as independent variables in the second model produced a regression coefficients (b) of - 49.166 for traffic, and 0.148 for two previous winters precipitation (Table 2.7). Both variables in the second model significantly influenced the number of fires (P = < .001). The second model had an R^2 value of .59, and a standard error of the estimate (SE) of 36.65 (Table 2.7).

Two consecutive winters and consecutive winter and summer precipitation showed significant effects on the number of fires (Appendix E), but did not have a strong regression coefficient. The final model for number of fires is (y) = - 49.166 + .0066 traffic + .148 three consecutive winters precipitation.

Only one independent variable was selected in the stepwise regression process for predicting hectares burned. Three consecutive winters precipitation had a significant regression coefficient (P = <.001) of 9.137 (Table 2.7). The R^2 was .50 and SE 36.65 for the model. The "F" test shows the model to be highly significant (P=< .001). The final model for predicting hectares burned was: Hectares burned (y) = -2335.606 + 9.137 three consecutive winters precipitation.

Table 2.5. Summary of the person caused fires and *El Niño* years in relationship to the number of fires and hectares burned in the Sonoran Desert on the Tonto National Forest from 1955 through 1999.

Year	Number of Fires	Hectares Burned	Number of person caused fires	Percent person caused	ENSO Phase
1955	3	.12	2	66.67	SL
1956	9	492.31	5	55.56	LN
1957	3	45.73	0	.00	EN
1958	21	285.80	9	42.86	N
1959	12	3397.17	5	41.67	N
1960	11	4.82	7	63.64	N
1961	9	30.64	6	66.67	N
1962	8	20.92	5	62.50	N
1963	15	9.59	15	100.00	EN
1964	8	14.25	5	62.50	LN
1965	16	64.71	11	68.75	SE
1966	33	726.91	29	87.88	N
1967	8	7.57	7	87.50	N
1968	5	3.93	3	60.00	N
1969	44	557.55	35	79.55	EN
1970	33	292.31	23	69.70	LN
1971	15	44.21	11	73.33	LN
1972	16	1.00	16	100.00	SE
1973	80	387.39	54	67.50	SL
1974	53	1018.23	31	58.49	LN
1975	93	358.43	64	68.82	SL
1976	92	2949.41	59	64.13	EN
1977	49	63.13	40	81.63	SE
1978	59	35.61	46	78.00	N
1979	133	16198.70	113	84.96	N
1980	218	9297.45	156	71.56	N
1981	141	382.44	102	72.34	N
1982	97	100.20	89	91.75	SE
1983	133	1912.04	104	78.20	N
1984	106	395.43	89	83.96	N
1985	120	193.44	93	77.50	N
1986	121	146.09	95	78.51	N
1987	108	261.84	78	72.22	SE
1988	189	3251.32	126	66.67	SL
1989	82	117.77	63	76.83	N
1990	43	21.45	33	76.74	N
1991	70	457.71	64	91.43	EN
1992	131	647.51	95	72.52	EN
1993	153	956.76	121	79.08	SE
1994	126	1976.97	79	62.70	SE
1995	125	6374.54	107	85.60	N
1996	65	39.09	54	83.08	N
1997	37	9.11	32	86.49	SE
1998	94	350.04	84	89.36	SL
1999	117	114.37	105	89.74	N
2000	68	38.4	60	8.00	
Mean	68.96	1175.10	51	69.78	

Note: ENSO phase is a (SOI) rating; SE= Stronger *El Niño*; EN= Moderate *El Niño*; N =neither; LN = Moderate *La Niña*; SL= Stronger *La Niña*.

Table 2.6. Summary of the person caused fires and El Niño years in relationship to the number of fires and hectares burned in the Sonoran Desert on the Tonto National Forest from 1955 through 1999.

Year	Number of Fires	Hectares Burned	Number of person caused fires	Percent person caused	ENSO Phase (Number of El Niño or Strong El Niño years in the decade)
1950s	9.6	844	4.2	41.4	1 EN
1960s	15.7	144	12.3	73.9	2 EN; 1 SE
1970s	62.3	2135	48.9	66.1	2 SE; 1EN
1980s	131.5	1606	99.5	77.0	2 SE
1990s	96.0	1095	77.4	81.7	2 EN; 3 SN

Note: ENSO phase is a (SOI) rating; SE = Stronger *El Niño*; EN = Moderate *El Niño*. Other years are either *La Niña* or neither.

Table 2.7. Results of the stepwise regression analysis evaluating the effects of nine variables on the number of fires and hectares burned.

	Model	Unstandardized Coefficients B	R^2	Standard error of the estimate	Sig.
		NUMBER OF FIRES			
1	(Constant)	-11.220			
	Highway traffic on SH_60 + SH_87	8.715E-03	.44	42.23	.000
2	(Constant)	-49.166			.004
	Highway traffic on SH_60 + SH_87	6.600E-03			.000
	Three consecutive winters precipitation	.148	.59	36.65	.000
		HECTARES BURNED			
	(Constant)	-2335.606			.027
3	Three consecutive winters precipitation	9.137	.25	2538.8	.001

Discussion

The Sonoran Desert is characterized by a bimodal rain pattern with highly variable winter-early spring precipitation (December-March), an arid late spring and early summer (April-June), with monsoonal rains in July and August, and a moderately dry autumn (September-November) Winter precipitation, when in sufficient quantity, recharges soil moisture and produces a crop of winter annual plants. However, the arid early summer dries and kills the plants to produce flammable fine fuels. Data from this study shows an interaction between the heavy anthropogenic activities, and arid early summer conditions preceded by one to three consecutive wet winters yields a vigorous fire season in late spring-early summer. The summer monsoons sharply reduce the incidence of fire in the Sonoran Desert by increasing fuel moisture and unfavorable fire conditions such as increased relative humidity. The concentrated anthropogenic activities and arid early summer conditions are the most consistent of the three variables in the Sonoran Desert fire regime. Winter precipitation is the most variable parameter, therefore, the number of hectares is most dependent on winter moisture. The strongest influence found on the number of fires and hectares burned was three consecutive winters of precipitation (Table 2.7, Fig. 2.5). The years which had above average precipitation during the winter were: 1965-67, 1978-82, 1985, 1992-95, 1998 and 1999. These years correspond well with the years that had above average hectares burned (> 1200 acres, Table 2.5). There results agree with those of Rogers and Vint (1987) in their work concerning fire in the Sonoran Desert.

The number of fires and hectares burned were positively influence by the *El Niño* events. The period from October through March tends to be wetter than usual following an *El Niño* event consequently the number of Sonoran Desert fires and hectares burned increased following an *El Niño* year. This was consistent with the findings in the work completed by Brazel and Ellis (in press). They analyzed the effect of the multivariate ENSO (MEI) and Southern oscillation indices on several key variables in the Central Arizona and Phoenix Long-Term Ecological Research Site (CAPLTER). The CAPLTER is in to the Sonoran Desert on the Tonto National Forest. Brazel and Ellis (in press) found a positive correlation between MEI values and mean CAPLTER monthly

precipitation. They found an increase in precipitation during the period fall through spring period during El Niño years. During these periods, high (low) MEI values corresponding with *El Niño* (*La Niña*) conditions were associated with greater (small amounts of precipitation across the CAPTER are (Brazel and Ellis, in press).

CHAPTER 3

THE EFFECTS OF FIRE ON SONORAN DESERT PLANT COMMUNITIES ON A TIME-SINCE-FIRE GRADIENT

Introduction

During the past two to three decades fire has caused widespread disturbance to native flora in some areas of the Sonoran Desert. Saguaro (*Carnegiea gigantea*) and many desert perennials that characterize the landscape have been eliminated from fire prone areas along major highways. Researchers have reported that the occurrence of fire in many areas of the Sonoran Desert has increased (Rogers 1986, Wilson et al. 1995, Narog et al. 1996, Smith et al. 1997) and could threaten the survival of native Sonoran Desert vegetation.

Fire is an important component of many upland ecosystems. Fire dependent ecosystems, such as ponderosa pine (*Pinus ponderosa*) and many grasslands, are characterized by fire adapted plant species that are maintained by fire disturbance (Swetnam and Betancourt 1998). However, fire is not likely a significant component in the evolutionary history of the Sonoran Desert (Humphrey 1974, McLaughlin and Bowers 1982, Patten and Cave 1984, Barbour et al. 1999). Fire basically defoliates and kills individual plants and leaves open patches for colonization with rapidly growing, fire tolerant species. These fire tolerant species enhance the fire cycle by providing fine, highly flammable material, during some years, that readily carries fire (Sage 1996, DeBano et al. 1998). Because of the discontinuous spacing of desert plants, and lack of fire adapted characteristics in native succulent plants, it is assumed that fires were infrequent in the long-term evolutionary history in most Sonoran Desert plant communities (Humphrey 1974, Rogers 1986, Smith et al. 1997). Desert perennials such as creosote bush (*Larrea tridentada*), bursage (*Ambrosia dumosa*), cholla and prickly pear (*Opunita* spp), white ratany (*Krameria grayi*), foothill palo verde (*Cercidium microphyllum*) and saguaro suffer high rates of mortality and do not readily return to post-burn communities (Rogers and Steel 1980, Cave and Patten 1984, Loftin 1987, Griffith 1991, Sweat 1995, Smith et al. 1997).

The recurrence of fire in the Sonoran Desert has often had the effect of changing the vegetation type from a shrub/cacti type to an annual grass type (McLaughlin and Bowers 1982, Cave and Patten 1984, Rogers 1986, D'Antonio and Vitousek 1992, Wilson et al. 1995, Narog 1996, Smith et al. 1997). This vegetative type conversion could cause a long-term increase in surface soil temperature, and drying of the soil. The drying condition, due to lack of vegetation cover, would cause a self regulating feed back scenario in which vegetation cover, diversity and production of biomass would decline and potentially cause a decrease in the net primary productivity of the ecosystem (Shreve 1936, Lowe and Hinds 1971, Barbour et al. 1999, Heitschmidt and Stuth 1991, Kimmins 1997). Balling et al. (1998) found that reduced ground cover and land degradation in a semiarid region in northern Mexico created surface temperatures and near surface air temperatures that were 2^0 C higher, and albedo 0.18 – 0.03 higher than the Arizona side of the border where the ground cover was greater. They concluded that despite having a higher albedo caused by the degradation of the landscape, the Mexican side of the border appeared to have warmed with respect to adjacent lands in Arizona. A decrease in soil moisture in Mexico has apparently disrupted the surface energy balance, reducing energy expended for evaporation and increasing energy for heating the surface and the lower atmosphere.

Documentation is available on the effects of fire on individual plant species in the Sonoran Desert. However, very little information is available to evaluate the recovery of individual species in communities over time. The purpose of this study is to determine the recovery of Sonoran Desert plant species on a time-since-fire (tsf) gradient and to ascertain the impacts of the fires on vegetation structure.

Methods

Study Area

The study area consists of five burned sites in the Arizona upland subdivision of the Sonoran Desert on the Tonto National Forest. The burn sites fit into five categories based on time-since-

fire (tsf): < 5 tsf, 5 – 10 tsf, 15 – 20 tsf, 20 – 25 tsf, and repeated burns (Table 3.1). The sites were selected based on their consistency with respect to physical and botanical factors. Elevation, precipitation, topography and soil classification are similar on all sites, and the sites are homogeneous with respect to species composition, cover and density (determined by ocular estimate). All study sites are located on upland *bajadas* with thermic or hyper thermic deep Typic Haplargid soils, and the elevation ranges between 610 and 650 m. Dominant perennial species in the control sites are saguaro, paloverde, creosote bush, bursage, cholla, prickly pear, white thorn acacia and cat claw acacia. The homogeneity of Sonoran Desert native plants among the study sites will allow isolation of tsf as a factor in evaluating the effects of fire on native plant communities in the Arizona Upland Sonoran Desert.

The River, Vista and Bush Highway Fires are located ca. 45 km north of Mesa, Arizona (Fig. 3.1), north of Forest Road 204 (Bush Highway), east of State Highway 87 (Beeline Highway), and south of Forest Roads 143 and 401 (Four Peaks and Cottonwood Canyon Roads, Fig. 3.1 and Fig. 3.2). The area is influenced by heavy use by off road vehicles, shooting, and camping, as well as frequent traffic along SH 87.

The study plots for the River Fire (5 tsf) were established on the northeast edge of the fire, where Forest Road 143 served as a fuel break and a boundary between the burned and control areas (Fig. 3.2). The plots are located in biophysically similar areas. Burned and unburned plots are physically separated by a road (Fig. 3.3).

The Vista Fire (7 tsf) originated at the Vista rest stop (recently removed) along SH 87 and burned east to FR 1863 which runs parallel to SH 87 about one half mile east. FR 1863 served as a fuel break and stopped the fire from continuing east. The burned plots were located west of FR 1863 (Fig. 3.4). The control plots were located on both the east side of FR 1863, and west of SH 87 (Figs. 3.2, 3.5 and 3.5).

The Bush Highway Fire (repeated fires) study plots were located at the southeast corner of the intersection of the Bush Highway and SH 87 (Fig. 3.2). The area is strongly influenced by

Table 3.1. A description of the study sites.

Study Site	Location UTM Coordinates	Elevation (m)	Year Burned	Fire age category Time-since-fire (tsf)	Time of Year Burned	Hectares Burned
River Fire	12-456596.4 S-3721442.6	610	1995	< 5 years	July	3845
Vista Fire	12-453154.6 S-3725095.2	650	1993	5 – 15 years	May	36
Bush Highway Fire	12-448178.0 S-3720636.7	635	1976, 1983, 1993, 1994	Repeat burns	May and June	40-200
Massacre Fire	12-455921.5 S-3701262.4	640	1983	15 – 20 years	July	1335
Siphon Fire	12-456564.9 S-3698264.8	618	1979	20 – 25 years	June	283

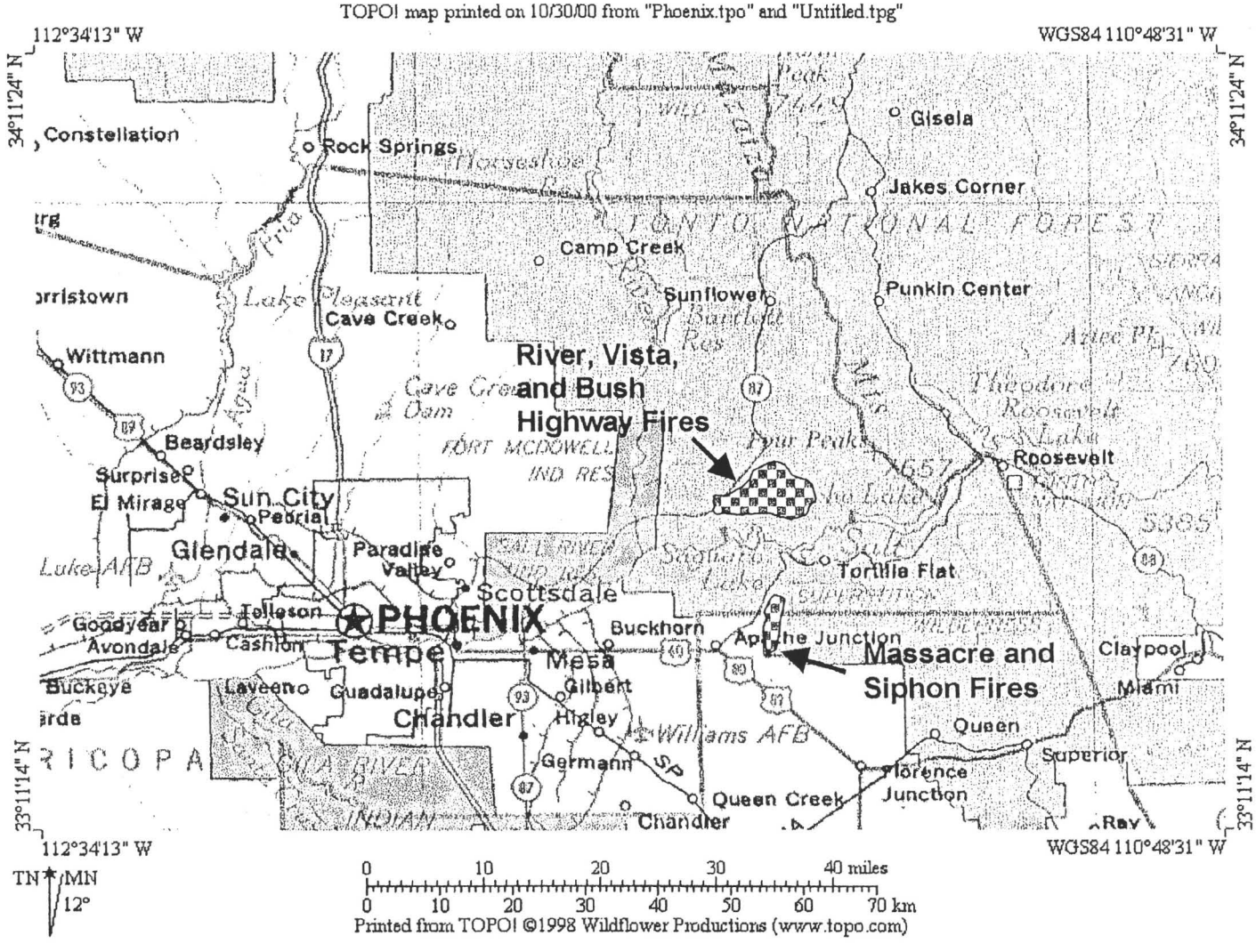


Figure 3.1. General locations of the study sites are designated by the red-checkered pattern.

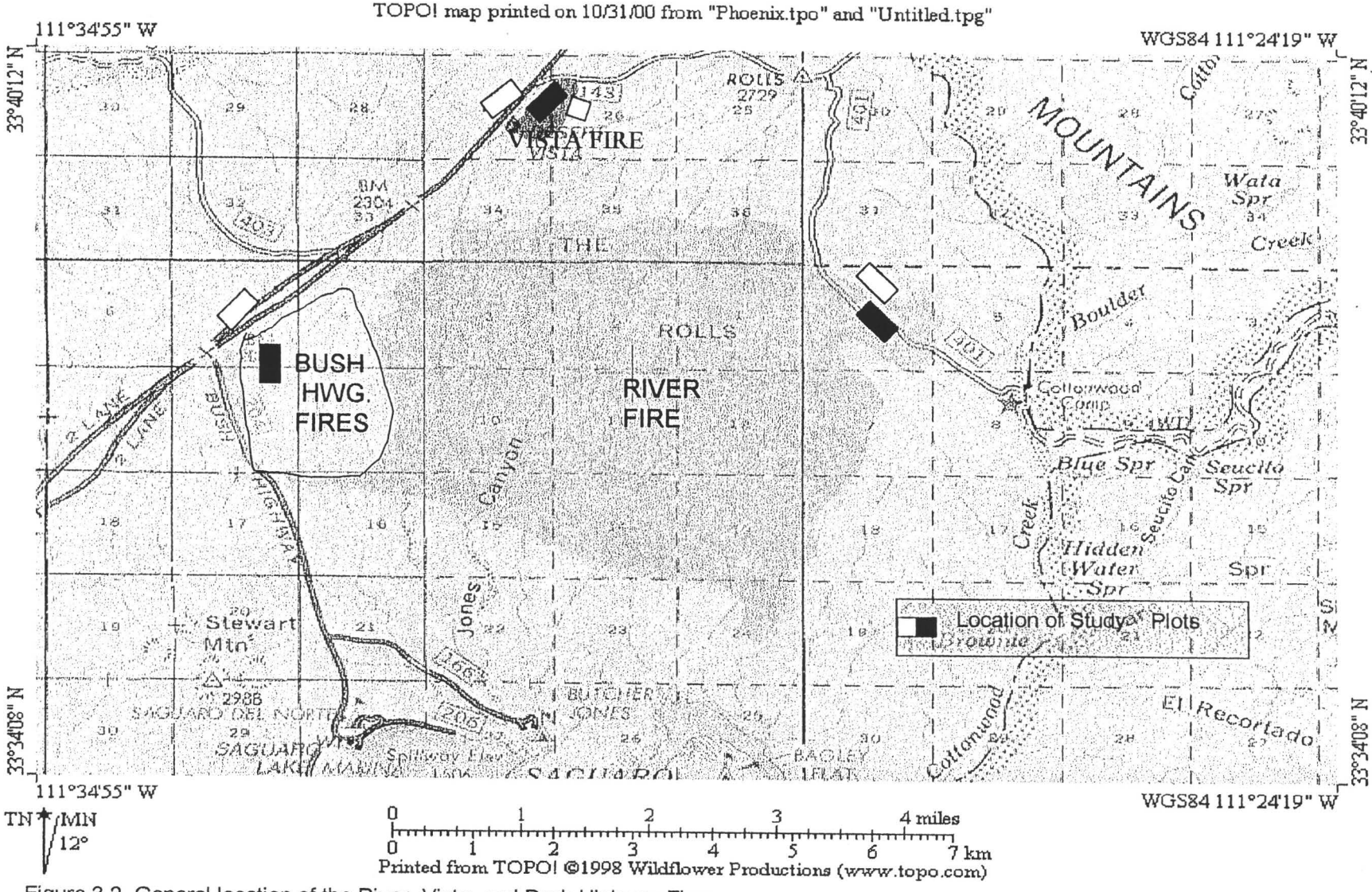


Figure 3.2. General location of the River, Vista, and Bush Highway Fires

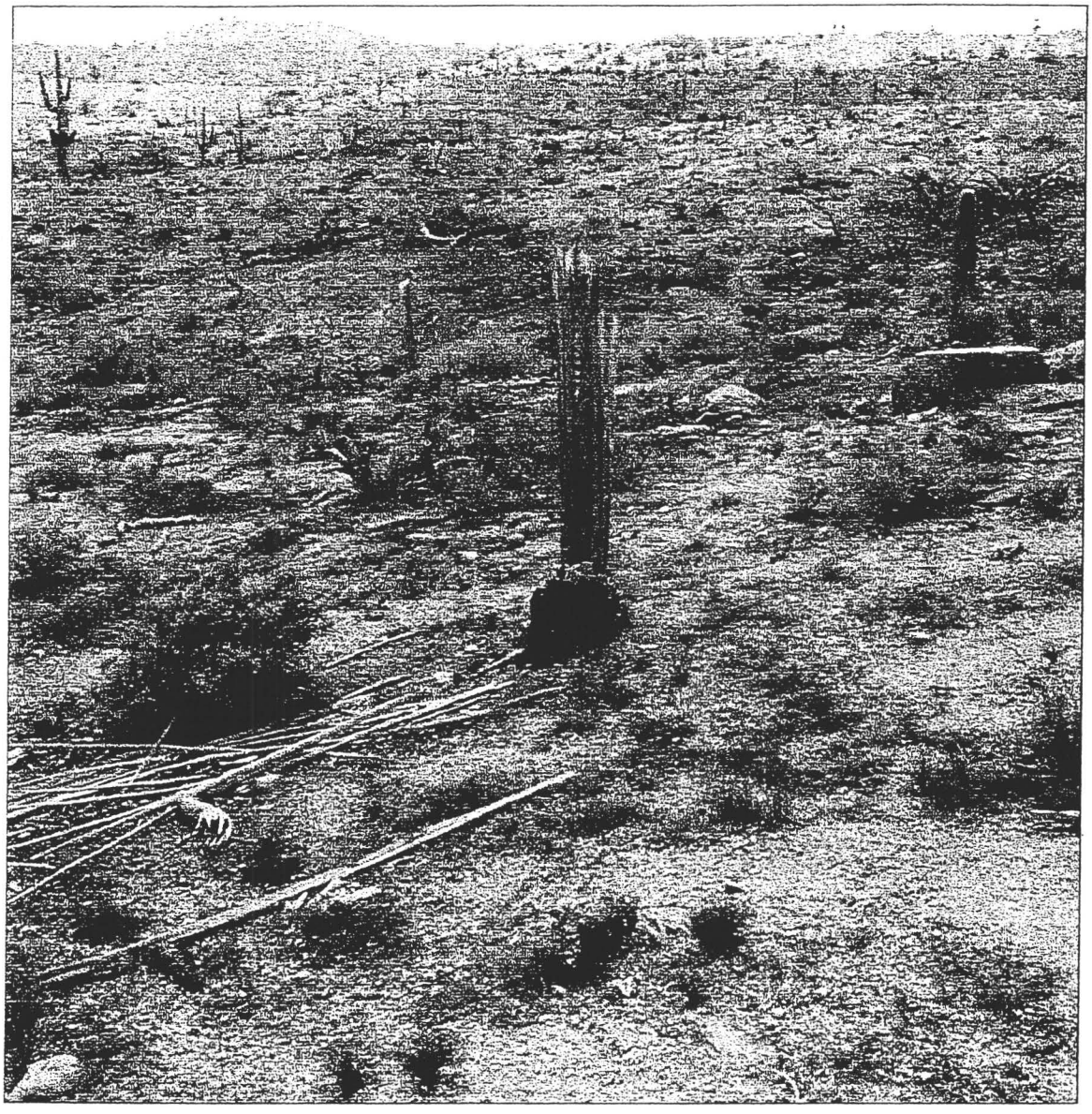


Figure 3.3. Burned area of the River Fire (< 5 years time-since fire), plot number 1.

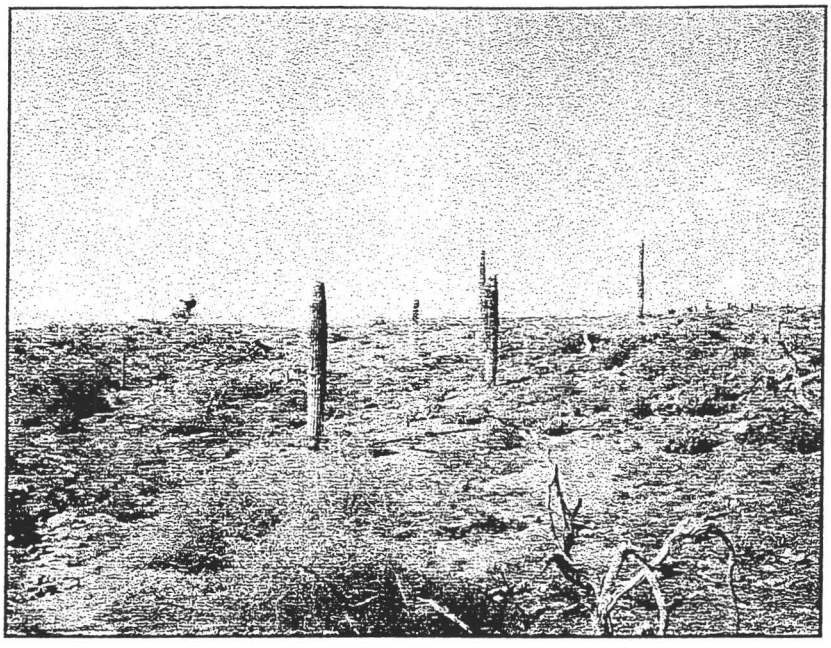


Fig. 3.4. The burned plot of the Vista Fire (5 – 15 tsf), located west of FR 1863, shows damage to *Carnegiea*, however, they have survived for seven years when this photo was taken.

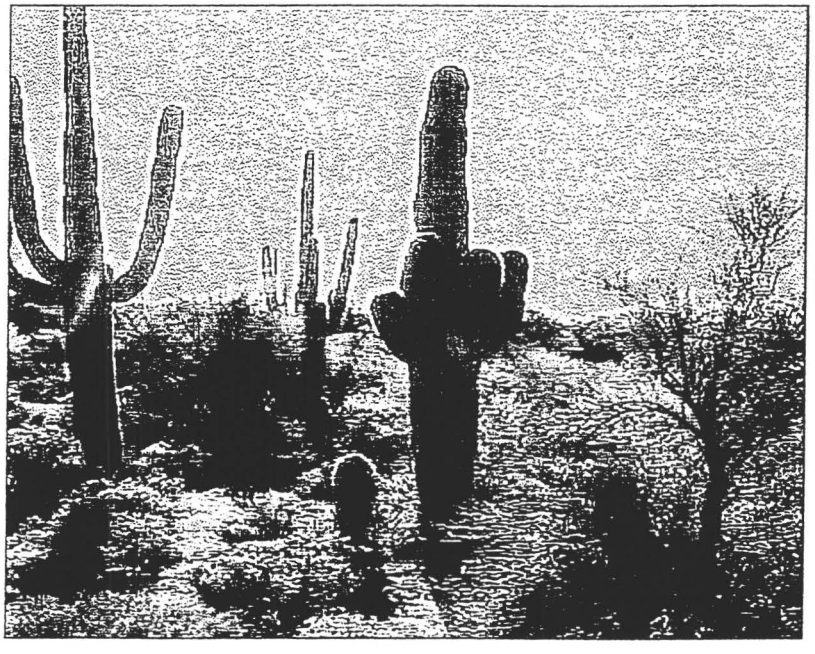


Fig. 3.5. Vista Fire control plot (unburned), located east of FR 1863. The plot supports good age class diversity of *Carnegiea* and *Cercidium*.

highway traffic and vehicle parking, and has burned four times during the past 3 decades. The control plots for the Bush Highway site were located on the west side of SH 87. Vehicles and people traveling on SH 87 are often an ignition source for fires, and since the prevailing winds are from the west to the east in this area most fires are on the east (leeward) side of SH 87.

The Massacre (17 tsf) and Siphon (21 tsf) fires (occurred east of Apache Junction, Arizona on the Tonto National Forest (Fig. 3.1). The fires extend from the base of the Superstition Mountains to the Tonto National Forest-Apache Junction boundary (Fig. 3.6). The area is adjacent to the Superstition wilderness, and is not heavily influenced by adjacent vehicular traffic. However, it is impacted by the activities of adjacent residents of Apache Junction. Historically there have been numerous fires started by residents burning garbage on private land, and children playing with matches or fire works, based on the Forest Service fire reports and articles from the *Apache Sentinel* newspaper.

The Siphon Fire (21 tsf) study area supports stands of diverse aged foothill paloverde, saguaro, desert hackberry (*Celtis pallida*) Torr., and wolfberry (*Lycium spp.*) (Figs. 3.7 and 3.8). The plots of the Massacre fire are located on the TNF, southeast of the Lost Dutchman State Park along recreation trail number 58. The control plots are located west of the trail between the trail and the private land in Apache Junction where it has been protected from fire due to the proximity of private homes (Fig. 3.6) .

The soils in the burned plot of the River Fire were classified as loamy skeletal, mixed, thermic, deep Typic Haplargids (Fig. 3.9). The control plots had a thicker "A" horizon and less surface sheet and rill erosion, but the same soil classification (Steinke 2000, unpublished data). Soils on the burned plots of the Vista fire were fine-loamy, mixed, active, thermic, Typic Haplargids, with the top 11 cm of the surface being compacted (Ambos 2000 unpublished data). The control plots of the Vista fire were coarse-loamy, mixed, active, thermic Typic Haplargids, with the top 9 cm being compacted.

The Massacre and Siphon fires are located on *bajadas* dissected with large volcanic bolder fields from the canyons in the Superstition Mountains. The soils in the Siphon plots were

classified as loamy-skeletal, mixed, super active, hyperthermic Typic Haplargids. The soils were deep with a very bouldery loamy sand surface horizon. The soils in the Massacre plots were similar to the soils in the Siphon plots except the Massacre plots had an extremely bouldery, sandy loam surface horizon. Many more boulders were observed in the Massacre fire than the Siphon fire. The soils on the Massacre Plots appeared to be slightly warmer than the soils on the River and Vista fires based on the presence of ironwood which indicates a hyperthermic soil temperature instead of thermic (Ambos 2000, personal communication).

Field Data Collection

There is a high level of innate variability in Sonoran Desert plant communities, and the effects of fire is highly variable depending on the consistency and intensity of the burn. Another dimension that adds complexity to evaluating the effects of fire, is the long recovery time required for Sonoran Desert vegetation after fire. For these reasons, large study areas, high numbers of replications, and long periods of time are needed to accurately measure the effects of fire. In order to isolate the measurements to the variation caused by fire, the ideal experimental design would involve measuring an area before the burn, burning the area, and then measuring the vegetation for a period of years and intervals of years. However, this approach was not feasible and the time required is not practical. Therefore, wildfires that have burned over time were used to measure the effects of fire.

A random-systematic design (Barbour et al. 1999) was used to compare plant height, cover and density between burned and control plots in five areas in the Sonoran Desert. Five 100 m X 100 m (one hectare) homogeneous macro plots were located within the burned area of each study site, and in adjacent control areas. Within each macro plot, four randomly located 100 m transects were established. Canopy cover was measured by the line intercept method, in which the length of the intercept of canopy was measured for each species (Cox 1996). The height of each plant that intersected the line was recorded. The same 100 m line was used to form the center of a 2 m X 100 m belt transect. Density was estimated by counting the number trees,

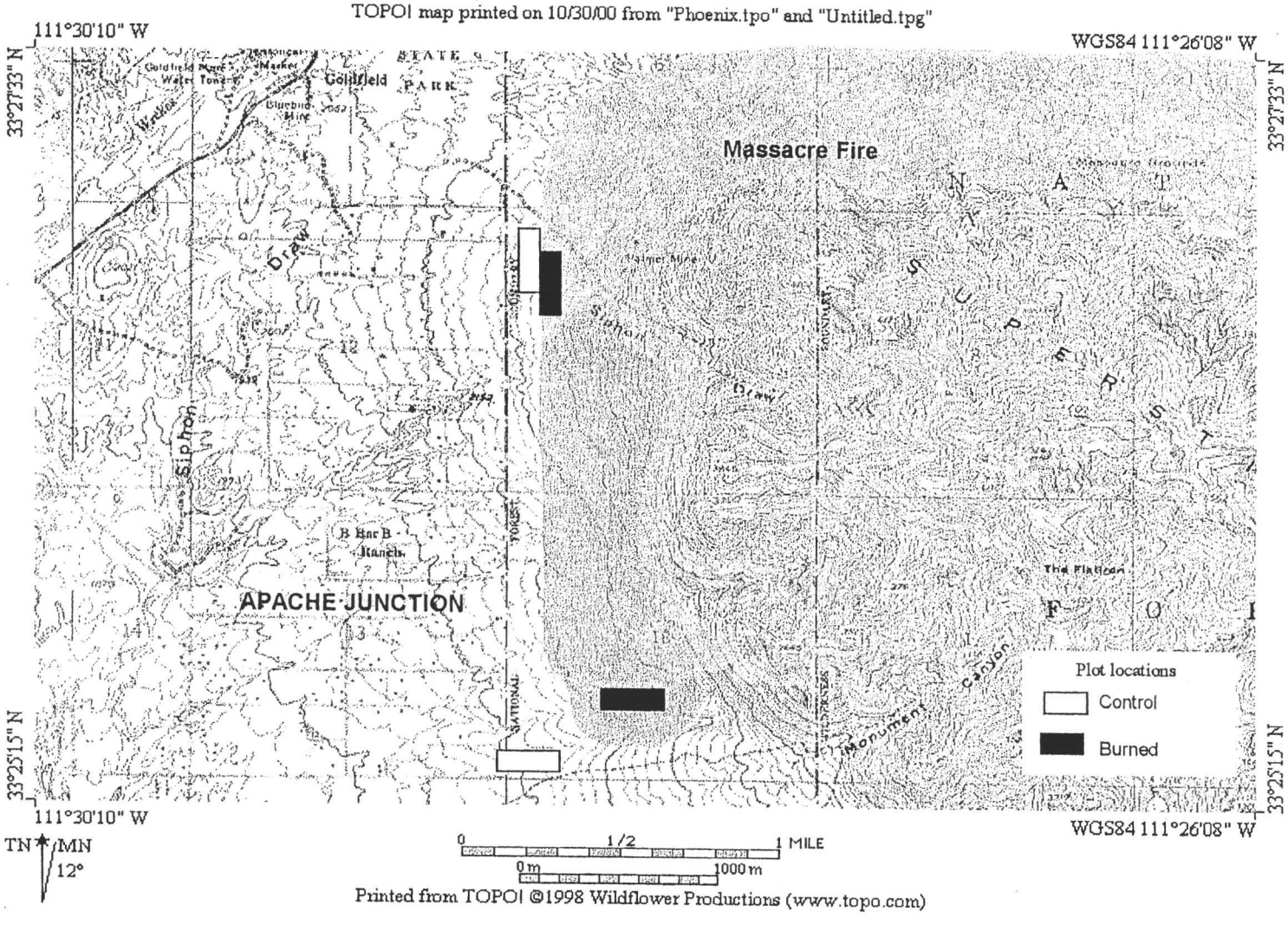


Figure 3.6. Location of the Massacre and Siphon Fires

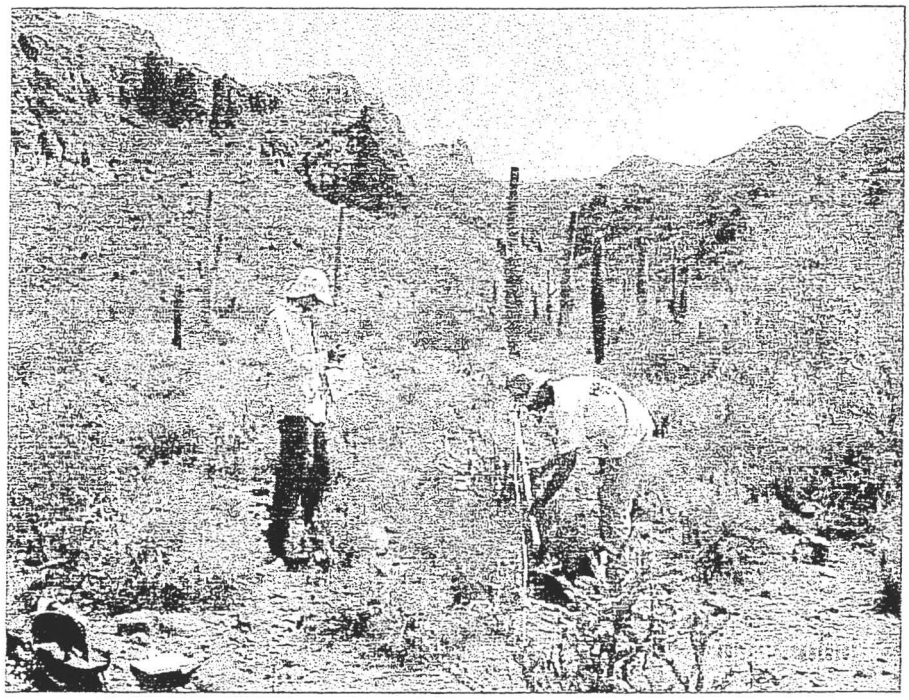


Fig. 3.7. Burned plot of the Siphon Fire.

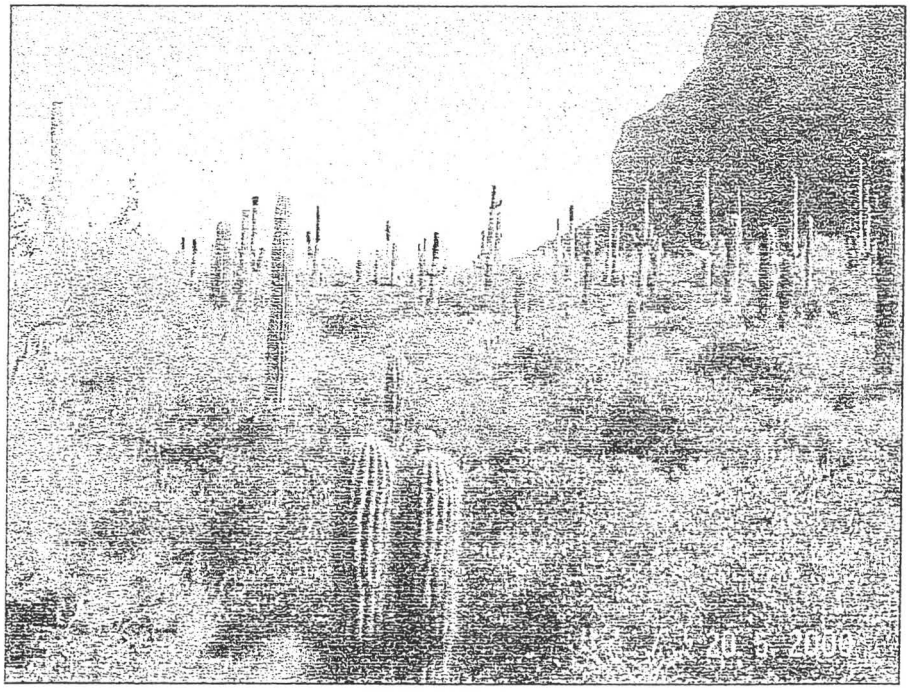


Fig. 3.8. Control plot for the Siphon Fire study area.

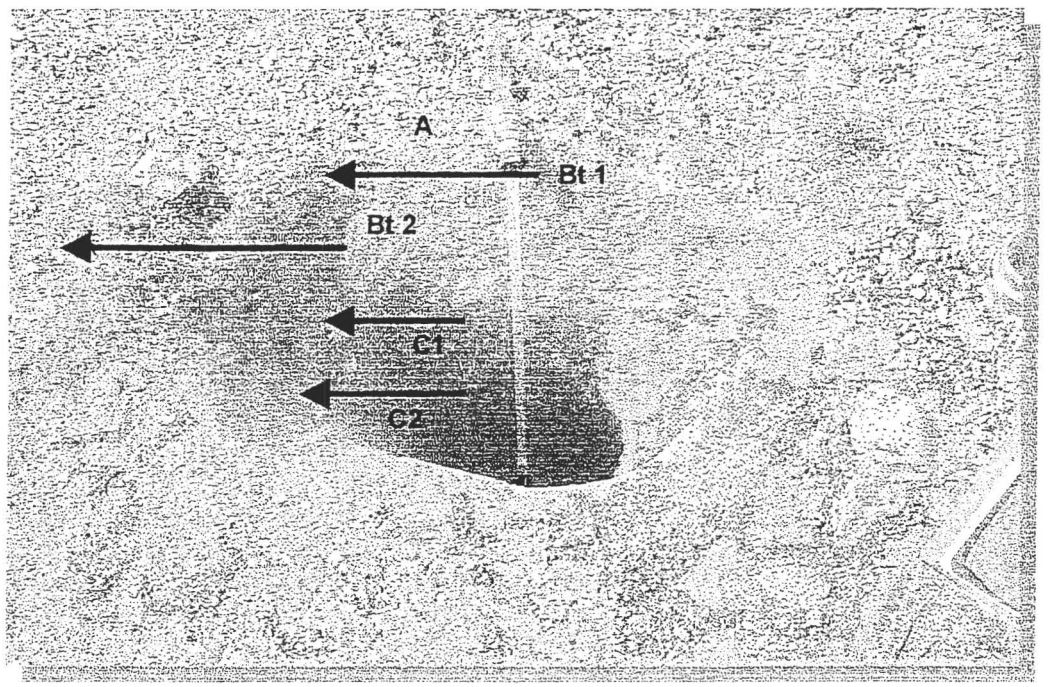


Figure 3.9. Photograph of a soil classification pit a burned plot of the River Fire. ("Typic Haplargids, loamy-skeletal, mixed, thermic, deep)

shrubs and perennial plants in the belt transects. The number of saguaro was counted within each 100m X 100m macro plot. The treatment areas are the burned areas in which the recent fire history is known. The control areas are generally recognized as having no recent fire history, or evidence of being burned in recent history (>50 years).

Cover similarity was determined by calculating the percentage of cover in the burned area of the control areas (cover similarity = burned area cover / control cover).

Field data were collected from March through June, 2000. The sequence of data collection from each of the fires was: The River Fire, Vista Fire, Bush Highway Fires, Siphon Fire and Massacre Fire. Because of dry winter conditions during the year 2000, the production of winter annual vegetation was almost non-existent, and most measurements were recorded on perennial shrubs and half shrubs. Therefore, the variation in measurements between the earliest dates of data collection and the latest dates was not a concern.

The scientific names used to identify plants are according to Lehr (1978). Plants found in the macro plots are listed in Table 3.2.

Statistical analysis

The paired student "t" test program of the SPSS Base 10.0 software was used to compare the mean height, cover and density of each species between the control and burned treatments of each fire (study area). The pooled "t" test (Zar 1996) was used to compare the height, cover and density of burned and control plots. The five plots in each of the treatment areas and in the control areas served as replications in the study. The pooled "t" test determined if there was a significant difference ($P = < 0.05$) in cover and density.

Results

Effects on Plant Communities

The number of perennial species in the burned plots versus the control plots were similar in all of the fires except the Vista (7 tsf) and Bush Highway (repeated) fires (Table 3.3). The Vista

Table 3.2. Plants found in the macro study plots. Scientific names are consistent with Lehr (1978).

Scientific name	Common Name
Acacia greggii Gray	cat-claw acacia
Acacia constricta Benth	white-thorn acacia
Ambrosia deltoidea Torr	bursage
Aristida purpurea	purple three-awn
Bebbia juncea (Benth.) Greene	chuckawalla's delight
Calliandra eriophylla Benth	false-mesquite
Carnegiea gigantea (Engelm.) Britt. & Rose	saguaro
Cassia armata Wats.	senna
Echinocerus pectinatus (Scheidw.) Engelm.	hedgehog cactus
Ecinocerus englemanni Parry	hedgehog
Euphorbia antisi	candelina
Celtis spinosa Torr	desert hackberry
Cercidium microphyllum (Torr.) Rose & Johnston	foothill paloverde
Dodonaea viscosa Jacq	hopbush
Encelia farinosa Gray	Brittle bush
Encelia frutescens Gray	rayless *Encelia*
Ericameria cooperi	turpentine bush
Eriogonum fasciculatum Benth.	flat-top buckwheat-brush
Janusia gracilis Gray	odora
Koeberlinia spinosa Zucc.	all thorn
Krameria parvifolia Benth.	range ratany
Krameria grayi Rose & Painter	white ratany
Larrea tridentada (DC.) Coville	creosote bush
Lotus rigidus (Bentth.) Green	desert rock pea
Lycium berlandieri Dunal.	wolfberry
Muhlenbergia porterii Scribn.	bush muhly
Opuntia fulgida Engelm	jumping cholla
Opuntia biglovii Engelm	teddy bear cholla
Opuntia leptocaulis DC.	desert Christmas cactus
Opuntia englemanii Engelm	englelman prickly pear
Opuntia versicolor Engelm	staghorn cholla
Porophyllum gracile Benth.	odora
Simmondsia chinensis (Link) Schneid.	jojoba
Sphaeralcea subhastata Coult	globe mallow
Yucca baccata Torr.	banana yucca
Ziziphus obtusifolia (Hook. Ex. T&G.) A. Gray	gray thorn

fire (7 tsf) had a total of 36 species in the control plots, and 43 in the burned plots. The Bush Highway fire (repeated burns) supported fewer species in the burned plots than the control plots (29 and 19 species, respectively). The high cover of purple three-awn (*Aristida purpurea*) influenced the number of species in burned plots of the Bush Highway fire. Purple three-awn occupied space and crowded out other herbaceous species in the burned plots, but did not exist in the control plots. The burned plots of the Vista Fire, as well as the River Fire supported a higher number of small herbaceous plants than the control plots. These plants included desert rock pea (*Lotus* spp), odora (*Porophyllum gracile*) white ratany (*Krameria grayi*), desert globe mallow (*Sphaeralcea ambigua*), and desert senna (*Cassia armata*). Buffelgrass (*Pennisetum ciliare*) was found in one of the burned plots next to SH 87 right-of-way. Although plant density of Buffelgrass was insignificant ($P = < 0.05$) it is an exotic grass that readily carries fire into the Sonoran Desert (McNamee 1996).

Mean plant height, canopy cover and density of all perennial species in each of the fires are summarized in Table 3.4. Plant height was greater ($P = < 0.05$) in the control plots in all but the Massacre (17 tsf) and Siphon fires (21 tsf). Plant height would be expected to be greater in the control plots of the more recent burns i.e. the River (5 tsf), Vista (7 tsf) and Bush Highway (repeated burns) fires. However, height measurement did not necessarily reflect the re-growth of plants after they were burned. The height measurements were taken on the live plants in both control and burned plots. Many of the tree-like species in the more recent burned fires (< 15 tsf), were protected from the fire and were not burned. The plants protected from fire could benefit by adjacent plants being removed by fire. The purpose of the height measurements were used to analyze the difference in the mean height of all plants in the burned versus the control plots.

The mean canopy cover was significantly higher ($P = <0.05$) in the unburned control plots of all fires (Table 3.4). The similarity of canopy cover between control plots and burned plots increased as tsf increased (Table 3.5, Fig. 3.10). The regression model for similarity of cover as one progresses from five years tsf to 21 years tsf is $y = 27.98 + 2.16\ x$ (where x = tsf ; $R^2 = .82$).

Table 3.3. Total number of perennial plant species found in the burned and unburned plots of each of the fires studied.

Name of Fire	Treatment	Total Number of Species
River Fire (< 5 tsf)	Control	33
	Burned	34
Vista (5 – 10 tsf)	Control	36
	Burned	43
Bush Highway (repeated fires)	Control	29
	Burned	19
Massacre (10 – 15 tsf)	Control	12
	Burned	11
Siphon (15 – 25 tsf)	Control	14
	Burned	12

Table 3.4. Summary of total plant height (m), canopy cover (%) and plant density (#/hectare) measured in the burned and control plots on each of the fires.

Fire Name	Treatment	Plant Height	Canopy Cover	Plant Density
River(< 5 tsf)	Control	0.9	20.2	6046
	Burned	0.4	6.5	4838
	Difference	0.5	13.7	780
Vista (5 – 10 tsf)	Control	0.9	24.4	3305
	Burned	0.4	10.1	2142
	Difference	0.5	14.3	1163*
Bush Hwg. (repeated)	Control	1.4	31.3	3616
	Burned	1.0	16.6	11862
	Difference	0.4	14.7	-8246*
Massacre (10 – 15 tsf)	Control	0.5	20. 6	6757
	Burned	1.0	11.6	2899
	Difference	0.4	9.0	3858*
Siphon (15 – 25 tsf)	Control	1.2	40.4	6831
	Burned	1.4	31.3	5663
	Difference	-0.2	9.1	1168

* Significant (P = < 0.05)

Table 3.5. Canopy cover (%) comparison between the burned and control plots for fires in the upper Sonoran desert.

Fire Name	Canopy Cover (%)		
	Burned	Control	*Similarity (%)
River Fire (< 5 tsf)	6.5	20.2	33
Vista Fire (5 – 10 tsf)	10.1	24.4	42
Bush Highway Fire (repeated)	16.6	31.3	53
Massacre Fire (10 – 15 tsf)	11.6	20.6	57
Siphon Fire (15 – 25 tsf)	31.3	40.4	78

*Percent similarity = canopy cover control/canopy cover burned X 100

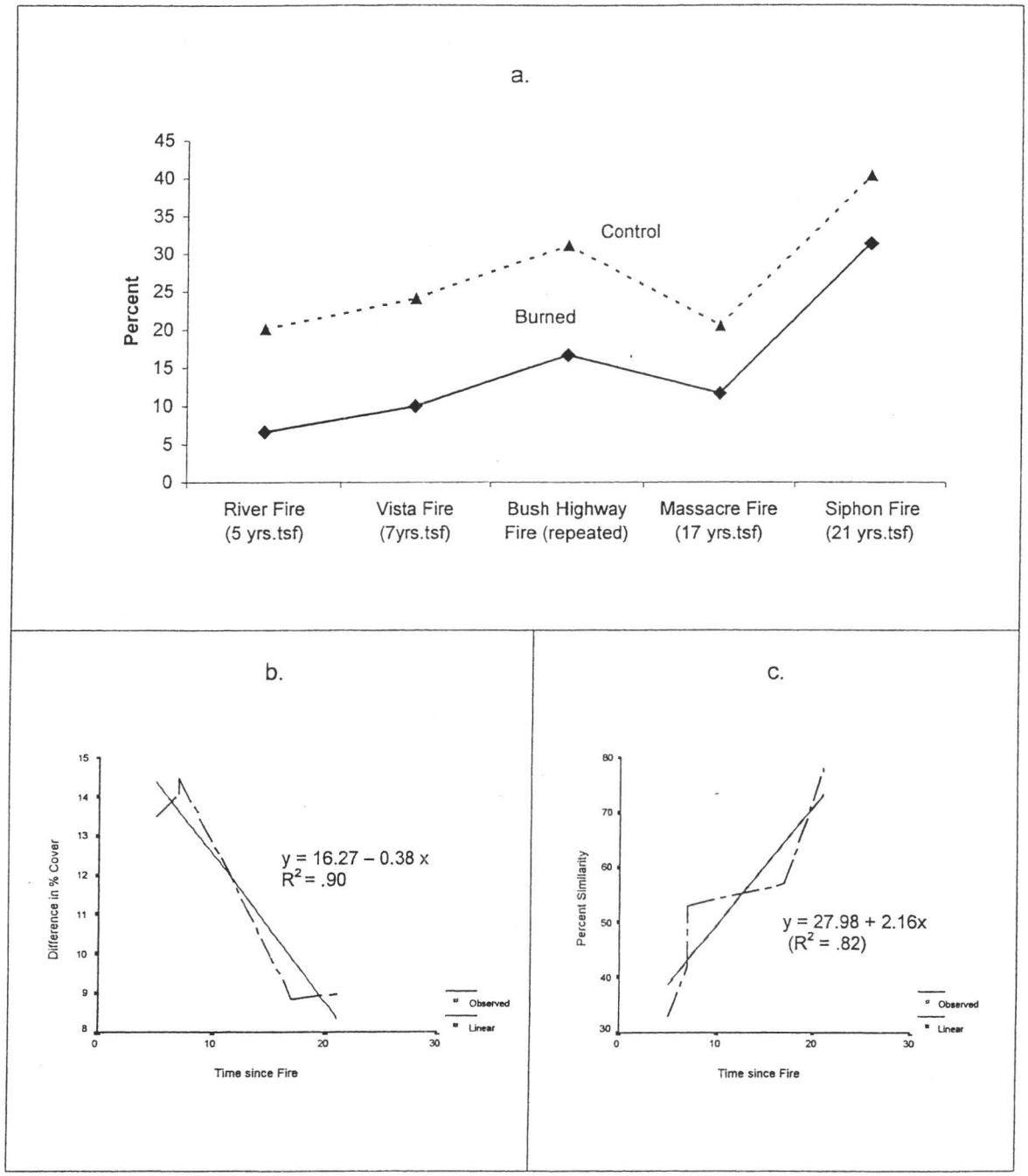


Fig. 3.10. Canopy cover response to tsf. a. shows the canopy cover of burned and control plots; b. shows the difference in canopy cover between control and burned plots on a tsf gradient; c. shows the similarity between the burned and control plots on a tsf gradient.

Total plant density was significantly greater (P=< 0.05) in the control plots of the Vista (7 tsf), and Massacre (17 tsf) fires. The Bush Highway plots supported a significantly higher (P = < 0.05) density in the burned plots primarily because of the common occurrence of purple three-awn (Table 3.6).

Fire effects on individual plants

Bursage, purple three-awn, foothill paloverde, white ratany, prickly pear, saguaro and false mesquite were greater (P = < 0.05) in density in the control plots of the River fire (5 tsf; Table 3.7). The same species, except for saguaro and false mesquite were also greater in cover in the control plots. The burned plots of the River fire supported greater cover of brittle brush and greater densities of brittle brush desert senna and creosote bush.

Bursage, desert senna, foothill palo verde, wolf berry and jojoba were greater in cover and density (P < 0.05) in the control plots of the Vista fire. Greater densities, but not cover, of saguaro and prickly pear were also measured in the control plots (Table 3.8). Greater cover (P < 0.05) of false mesquite and desert rock pea were found in the burned plots, and greater densities of wild buck wheat, creosote bush, false mesquite, desert rock and odora were measured in the burned plots (Table 3.8).

Bursage, wolfberry and jojoba were greater in cover in the control plots of the Massacre fire and densities were greater for bursage, wolfberry, jojoba, saguaro, and prickly pear in the control plots. The burned plots supported greater density of foot hill palo verde, and greater cover and density of purple three-awn, desert senna and brittle bush, and density of palo verde (P < 0.05; Table 3.9).

The control plots of the Siphon fire supported greater cover and density of bursage, purple three-awn, brittle brush and white ratany as well as greater density of jojoba. The burned plots supported greater cover and density of foothill paloverde and prickly pear as well as greater densities of cat-claw acacia and wild buck wheat (P < 0.05; Table 3.10).

Table 3.6. Summary of plant height (m), canopy cover (%) and plant density (number/hectare)on the Bush Highway fire (repeated burns).

Species	Height			Canopy Cover			Density		
	Control	Burned	Diff.	Control	Burned	Diff.	Control	Burned	Diff.
Cat-claw acacia	2.1	1.9	0.2	0.2	0.9	-0.7*	28	57	-29
White-thorn acacia	2.3	1.6	0.7	2.7	3.7	-1.0*	78	1035	-957*
Bursage	0.6	0.5	0.1	5.3	2.8	2.5*	1670	808	862*
Purple three-awn	0.4	0.4	0.0	0.1	4.4	-2.4*	25	5847	-5822*
False mesquite	0.6	0.7	-0.1	0.7	0.3	0.4*	255	80	175*
Saguaro							4.2	0	4*
Desert senna				0.0	1.0	-1.0	0.0	3518	-3518*
Foothill paloverde	3.4	1.2	2.2*	6.4	0.0	6.4*	110	8	102*
Brittle bush	0.7	0.8	-0.1	0.9	0.5	0.4	253	175	78
Buckwheat									
White ratany	0.7	0.5	0.2	1.9	0.5	1.4*	324	58	266*
Creosote bush	1.8	1.3	0.5	7.1	0.7	6.4*	458	33	425*
Desert rock pea									
Wolfberry	1.6	1.3	0.3	2.1	1.2	0.9*	200	113	87*
Engleman prickly pear	1.2	1.3	-0.1	3.9	1.6	2.3	210	130	80
**Species Summary	1.4	1.0	0.4	31.3	16.6	14.7	3615	11862	-8246

* Significant (P = < 0.05)

** Species summary is the mean height of all species in each treatment, cover and density are the species total species per hectare.

Table 3.7. Summary of plant height (m), canopy cover (%) and plant density (number/hectare)on the River fire (5 tsf).

Species	Height			Canopy Cover			Density		
	Control	Burned	Diff.	Control	Burned	Diff.	Control	Burned	Diff.
White-thorn acacia	1.8	0.9	0.9	1.6	1.3	.3	60	75	- 15
Bursage	0.2	0.4	-0.2	5.1	1.4	3.7*	1516	403	1113*
Purple three-awn	0.5	0.2	0.3	0.2	0.0	0.2*	186	84	102*
False-mesquite	0.5	0.2	-0.3	0.6	0.8	-0.2	1092	527	565*
Saguaro							30	13	17*
Desert senna				0.0	0.1	-0.1	44	200	-156*
Foothill paloverde	4.1	1.1	3.0 *	8.1	0.3	7.8*	199	30	166*
Brittle bush	1.1	0.4	0.7*	0.0	0.5	-0.5*	53	198	-145*
Buckwheat	0.4	0.3	0.1	0.5	0.4	0.1	380	379	1.0
White ratany	0.6	0.3	0.3*	1.0	0.5	0.5*	703	125	578*
Creosote bush	0.2	0.3	-0.1	0.6	0.3	0.3	866	2682	-1816*
Wolfberry	1.0	0.7	0.3	0.4	0.7	-0.3	25	49	-24
Engleman prickly pear	0.9	0.4	0.5	1.7	0.0	1.7*	311	7	303*
Odora	0.3	0.2	0.1	0.4	0.2	0.2	581	494	87
Species Summary	0.9	0.4	0.5	20.2	6.5	13.7	6046	5266	780

* = Significant (P = < 0.05)
** Species summary is the mean height of all species in each treatment, cover and density are the species total species per hectare.

Table 3.8. Summary of plant height (m), canopy cover (%) and plant density (number/hectare)on the Vista fire (7 tsf).

Species	Height			Canopy Cover			Density		
	Control	Burned	Diff.	Control	Burned	Diff.	Control	Burned	Diff.
White-thorn acacia	1.7	1.3	0.6	5.3	4.0	1.3	278	250	28
Bursage	0.6	0.3	0.3	3.8	0.4	3.4*	1178	203	975*
False-mesquite	0.3	0.4	-0.1	0.7	1.2	-0.5*	356	480	-124*
Saguaro							22	7	15*
Desert senna				0.3	0.0	0.3*	18	0	18*
Foothill paloverde	2.8	0.4	2.4*	7.5	0.1	7.4*	90	30	60*
Brittle bush				0.1	0.2	-0.1	33	28	5
Buckwheat	0.2	0.2	0.0	0.2	0.3	-0.1	403	470	-63*
White ratany	0.1	0.2	0.1	0.0	0.1	-0.1	10	13	-3
Creosote bush	0.6	0.2	0.4	0.8	0.6	0.2	8	25	-17*
Desert rock pea	0.1	0.1	0.0	0.1	0.2	-0.1*	5	125	-120*
Wolfberry	1.9	0.5	1.4	2.9	0.8	2.1*	278	50	228*
Engleman prickly pear				0.5	0.0	0.5	73	0	73*
Odora	0.3	0.1	0.2	0.1	0.9	0.8	33	253	-220*
Jojoba				0.2	0.0	0.2*	15	0	15*
Banana yucca				1.9	1.3	0.6	505	208	297*
**Species Summary	0.9	0.4	0.5	24.41	10.1	14.3	3305	2142	1163

* = Significant (P = < 0.05)
** Species summary is the mean height of all species in each treatment, cover and density are the species total species per hectare.

The Massacre fire supported higher canopy cover and density of bursage, wolfberry, and jojoba (Table 3.9). Density was also higher for prickly pear and saguaro in the control plots. The difference in canopy cover measurements prickly pear of were not significantly ($P = < 0.05$) different for. The burned plots supported significantly ($P = < 0.05$) higher cover and density of purple three-awn, desert senna and brittle bush.

The Siphon Fire supported greater canopy cover and density of bursage, purple three-awn, brittle bush, white ratany in the control plots (Table 3.10). Density of jojoba was greater in the control plots, but the difference in canopy cover was not significant ($P = < 0.05$).

Plant Recovery

Plant height and canopy cover increased as tsf increased. However, total density decreased slightly. Plant density was greatest on the Bush Highway (repeated burns) fire while canopy cover and height were lowest at this site. The effect of repeated fires appears to have caused an increased density of purple three-awn and other herbaceous plants, but deceased the number and size of shrubs.

There were no significant differences in height, cover, or density among shrubs and perennial plants between the control plots and the burned plots on the Siphon fire (21 tsf) except for white ratany, bursage, and prickly pear (Table 3.10). Canopy cover was greater in the control plots for white ratany, and bursage , and higher in the burned plots for prickly pear. This indicates that the plants in the Siphon fire (21 tsf) are nearer recovery than the other fires.

Table 3.9. Summary of plant height (m), canopy cover (%) and plant density (number/hectare)on the Massacre fire (17 tsf).

Species	Height			Canopy Cover			Density		
	Control	Burned	Diff.	Control	Burned	Diff.	Control	Burned	Diff.
White-thorn acacia									
Bursage				16.6	0.6	16.0*	6260	15	6245*
Purple three-awn				0.0	0.1	-0.1*	0.0	162	-217*
Saguaro							57	5	52*
Desert senna				0.0	0.1	-0.1*	0.0	162	-162*
Foothill paloverde							0.0	10	-10*
Brittle bush				0.0	9.6	-9.63*	0.0	2252	-2252*
Wolfberry	0.5	1.3	-0.8*	0.6	0.3	0.3*	150	91	59*
Engleman prickly pear	0.6	0.5	0.1	0.3	0.3	0.0	160	135	25*
Odora									
Jojoba	0.5	1.1	-0.6*	3.1	0.6	2.5*	130	67	63*
Species summary	0.5	1.0	-0.5	20.6	11.6	9.0	6757	2899	3858

* = Significant (P = < 0.05)
** Species summary is the mean height of all species in each treatment, cover and density are the species total species per hectare.

Table 3.10. Summary of plant height (m), canopy cover (%) and plant density (number/hectare)on the Siphon fire (21 tsf).

Species	Height			Canopy Cover			Density		
	Control	Burned	Diff.	Control	Burned	Diff.	Control	Burned	Diff.
Cat-claw acacia							0.0	3	-3*
Bursage	0.6	0.9	-0.3	24.8	14.6	10.2*	5700	4740	960*
Purple three-awn				1.1	0.0	1.1*	20	0	20*
Saguaro							77	66	11
Foothill paloverde	2.4	3.6	-1.2*	2.6	4.0	-1.4*	33	35	-2*
Brittle bush				0.2	0.0	0.2*	53	25	28*
Buckwheat							0.0	3	-2.6*
White ratany	0.5	0.8	-0.3	0.2	0.1	0.1*	90	15	75*
Wolfberry	1.0	1.2	-0.2	0.7	0.5	0.2	100	98	2
Engleman prickly pear	1.0	0.9	0.2	0.2	2.1	-1.9*	93	275	-182*
Jojoba	1.5	1.2	0.3	10.6	10.0	0.6	665	403	262*
**Species summary	1.2	1.4	-0.2	40.4	31.3	9.1	6831	5663	1168

* = Significant (P = < 0.05)
** Species summary is the mean height of all species in each treatment, cover and density are the species total species per hectare.

The height of individual saguaros were measured in the Siphon Fire plots. The Siphon Fire (21 tsf) supports high age-class diversity of saguaro in both burned and unburned areas. The burned areas had 32% of the saguaro in the height category of < 0.6 m; 20% 0.6 to 1.0 m; 22% 1.0 to 3.0 and 25% > 3.0 m (Table 3.11). The control plots had fewer small saguaro and a higher percentage in the mature (> 3.0 m) category.

Discussion

Plants That Increased With Fire

The species with higher density and cover in the burned plots are reported to be species that increase with fire (Sage 1996, Cave and Patten 1984). In this study purple three-awn, desert senna, brittle bush, cat-claw acacia were greater in either density or cover in the burned plots on at least one of the fires.

The repeated fires in the Bush Highway plots have resulted in an increase in cover and density of purple three-awn and senna. The burned study plots for the Bush Highway Fires (repeated) was the location of a range analysis study site for students at Arizona State University in 1974. Vegetation inventories conducted by the students showed that perennial grasses were not present in the burned study plots for the Bush Highway fire prior to 1974 (Whysong 2000, personal communication). In the spring of 2000, 5,847 plants per hectare, and 4.4 percent canopy cover were measured for purple three-awn in the burned plot compared to 25 plants per hectare and 0.06 percent canopy cover in the control plots. purple three-awn is a warm-season native perennial bunchgrass that is generally reduced by fire for several growing seasons (Hitchcock 1951, Cronquist et al. 1977, Westman 1981, Carlson et al. 1990). Purple three-awn recovers from fire by tillering, and by storing seeds below ground, where they are insulated from heat damage during fire events (Evans 1967, Trlica and Schuster 1969, Wright 1974, Kinucan and Smeins 1993). In the Bush Highway fire plots purple three-awn occupied the site as a ruderal species,

Table 3.11. Height measurements of saguaro in the Siphon Fire (20 – 25 tsf).

Height category (m)	Age Class	Percentage of Plants	
		Control	Burned
< 0.6	Juvenile	8	32
0.6 – 1.0	↓	10	20
1.0 – 3.0		26	22
> 3.0	Mature	56	25

which could indicate a type conversion from desert shrub to grassland (Grime 1979, Crawley 1997). According to a process described by Barbour et al. (1999), in a global sense, grass invasion promotes a cycle that changes a nonflammable, native-dominated woodland or shrubland into a persistent, nonnative dominated, flammable grassland.

Desert senna increased in density in the burned plots in the River (5 tsf), Bush Highway (repeated burns) and Massacre (17 tsf) fires. It is a native annual legume common to disturbed areas throughout its range (Tesky 1992). It is killed by fire, but generally increases in abundance after fire, and will decrease in the absence of fire or other disturbance. It is favored by frequent fire, and often forms extensive colonies along fire lines, roadside ditches, and old fields (Grelen et al. 1984).

Brittle bush appeared to increase in density and canopy cover in the burned areas, but only the Massacre Fire (17 tsf) showed a significant ($P = < 0.05$) increase in density and cover in the burned area. Brittle bush is known as an early colonizer of disturbed sites, often replacing long-lived perennials in post fire communities (Vasek 1979, Rogers and Steele 1980, Brown and Minnich 1986, Prose et al. 1987). Brittle bush is often top-killed or completely killed by fire; however, the wind-dispersed seeds readily invade post fire environments and often become well established (Brown and Minnich 1986, Loftin 1987). Recurrent fires select for short-lived desert shrubs such as brittle bush at the expense of long-lived species (Brown and Minnich 1986, Tesky 1993).

Plants Decreased With Fire

White ratany is a climax component of the Creosote bush-*Flourencia cernua* (creosote bush-tarbush) plant association (Griffith 1991). It is said to be consistent in the community at pre-disturbance and post-disturbance. White ratany has a well-developed root system that allows the plant to exploit the decreased albedo, and increased soil water and nutrient availability after fire to recover density quite rapidly. However, canopy cover values remain lower in the open shrub microhabitat than the more mesic tree microhabitat. With better soil moisture or in a more

mesic microhabitat, post fire canopy cover of white ratany can be greater than pre-fire cover (Loftin 1987, Griffith 1991). However, it significantly decreased after fire in the River, Bush Highway and Siphon sites.

Banana yucca is easily top-killed by fire (Howard 1998). However, the ability to root sprout has allowed it to survive and it sometimes dominate fire-prone ecosystems. It decreased after fire on the Vista site (the only fire that had a significant measurement of the plant).

The major indicators of fire effects were saguaro and foothill paloverde, which were consistently greater in density and cover in the control plots. Foothill paloverde is a climax species in the Sonoran Desert flora (Paysen et al. 1980, Moir 1983, Pavek 1994, Turner et al. 1995). All above ground parts are photosynthetic and concentrations of chlorophyll are actually higher in the stems than in the leaves (Adams and Strain 1968, Szarek and Woodhouse 1978). Consequently the thin-barked photosynthetic stems are killed by fire (Cave 1982). With cooler fires the surviving rootstocks will sprout following fire. Foothill paloverde may require 20 years to return to pre-fire plant densities and community species composition following fires in paloverde-saguaro communities (Rogers and Steele 1980, Cave 1982, Loftin 1987,).

The early growth of the seedlings of saguaro is very slow. After 2 or 3 years they are only a few mm in height, and after 10 years they are often not more than 1.5 to 2 cm in height (Steenberg and Lowe 1977). Later growth is so variable that the age of a plant 1 m high may be from 20 to 50 years. About 30 to 40 years are needed for a saguaro to reach 1 meter (Steenbergh and Lowe 1983, Pierson and Turner 1998). After a height of 2 to 3 m is reached, the growth rate is about 10 cm year $^{-1}$ in the main trunk and slightly less in the large branches (Steenbergh and Lowe 1983, Pierson and Turner 1998). The largest saguaro was estimated from the known growth rate to be from 150 to 200 years. Thirty-two percent of the saguaro (the smallest height category) would have germinated and grown since the Siphon Fire occurred 21 years ago. The Siphon Fire was the only burned area where the growth of new saguaro was observed.

Mature saguaro and existing seedlings are killed by fire (Thomas 1991, Pavek 1994). Some

studies may have underestimated the fire-induced mortality because of the lag time between injury by fire and time of death (Rogers 1985). Other long-term effects of fire on saguaro could be epidural browning. Turner and Funicelli (2000) described a phenomenon of browning initiating at the base of the saguaro, which spreads upward in the plant in succeeding years. The browning decreases the effective photosynthetic area and will eventually kill the saguaro. The condition is not well understood, but is believed to be caused by some type of disturbance to saguaro.

Post fire recovery of saguaro is dependent upon the exposure of individual plants to intense heat, and seed dispersal from unburned plants (Rogers 1985). Surviving saguaro with little or no injury will resume growth (Cave 1982). Small saguaro with less than 2-5 m height, with large amounts of fuel at the base do not survive. The nurse plant species also influence saguaro survival. Although desert fire temperatures are variable, fire temperatures beneath the nurse plant, foothill paloverde were lower than under bursage in a study by Cave (1982). However, foothill paloverde produces a taller plant and would produce larger flame heights.

Recurrence of fire will decrease the probability of native plant survival in the Sonoran Desert. Thomas (1991) estimated that the fire-free periods in the Sonoran Dessert were historically greater than 250 years. Saguaro would be eliminated under a fire frequency of less than 30 years (Rogers 1985) because of it's slow reproduction and growth rates. Saguaro and other stem succulents rarely exhibit recruitment from seed (Smith et al. 1997). Steenbergh and Lowe (1977) found only 0.03% of the seeds that were broadcast actually germinated and only 16 percent survived for one year and seven percent survived in two years. At the end of two years seedlings will be ca. 0.6 cm tall (Steenbergh and Lowe 1969), and at the age of 20 to 50 years the plant will be only about 1m tall. Reproduction begins when the saguaro is ca. 2.2m tall (Hutto et al. 1986, Steenbergh and Lowe 1977), and growth is very slow.

The dynamics between saguaro and its nurse plant foothill paloverde have some important implications concerning the fire risk to saguaro. Saguaro seedlings grow beneath shade of the foothill paloverde and eventually tower over it and compete for available water. The saguaro is the more competitive plant and kills the foothill paloverde (Vandermeer 1980, McAuliffe 1984).

The decadent foothill paloverde becomes a fuel source for fire, which could bring intense damaging flames to the saguaro.

White-thorn acacia, a long-lived species usually confined to washes in the Sonoran Desert (Pavek 1994, Herbel et al. 1985), and wolfberry, are killed by severe fire, but low to moderate-severity fires may only consume its aerial portions. Surviving plants sprout from the root clown following fire (Loftin 1987, Tesky 1993). Both shrubs may take many years to regain its former density on the burned sites (Rogers and Steele 1980). The density and canopy cover of wolfberry was reduced by fire in the Vista (5 tsf) and Bush Highway (repeated) fires, but were not significantly affected in the other fires. Cover for white-thorn acacia was not significantly affected by fire.

Jojoba appeared to be greater in both density and cover in the control plots; however, the differences were not statistically significant in this study. Jojoba is apparently unable to tolerate closed communities such as arroyo thickets, extensive creosote bush stands, and chaparral (Mathews 1994). It is normally found growing in full sunlight. Jojoba seedling establishment is associated with nurse plants over at least part of its range (Sherbrooke 1989). It readily sprouts from the root crown following less severe fires (Gentry 1958, Cave 1982, Thomas and Goodson 1992, Matthews 1994) and seeds may survive fire, which may account for observations in this study.

Conclusion

The number of plant species decreased as time since fire increased. However, canopy cover increased along the tsf gradient. The similarity of total canopy cover between the burned and control plots increased with time. Canopy cover on the burned plots was 24% of the control plots on the River Fire (5 tsf) whereas the similarity of canopy cover between burned and controlled plots was 75% on the Siphon Fire (21 tsf). With this model one could predict that total ground cover would recover after approximately 28 years. This, however, does not mean that full recovery of vegetation after fire would occur during this time.

Saguaro and foothill paloverde were noticeably removed by fire from the burned plots in all but the Siphon Fire, which showed no significant difference in density of saguaro and a small significant increase in density of foothill paloverde. It is difficult to conclude that saguaro has recovered on the Siphon Fire, since the pre-fire density is unknown and the recovery after fire is rare. However, 32 % of the saguaro in burned plots were < 0.6 m in height. It takes 30 to 40 years for the saguaro to reach 1 m in height (Steenbergh and Lowe 1983, Pierson and Turner 1998). Therefore plants that are 0.6 m should be 18 to 24 years old, within the time since the Siphon fire event. Included in the 32% of the saguaro that were < 0.6 m in height were well dispersed heights from a few centimeters up to 0.6 m. Therefore, it is concluded that there was at least some recovery of saguaro on the Siphon Fire.

The Bush Highway Fire (repeated) appears to be the site most influenced by fire because of the loss of native Sonoran Desert vegetation. The highly significant increase in density and/or canopy cover of purple three-awn and senna, and the decrease in native species such as saguaro, foothill paloverde, white ratany, creosote bush, wolfberry indicates that shrubs and nurse trees are being replaced with lower growing plants.

The plants that initially colonized the plots after fire, in the Sonoran Desert, have remained in the plant communities in each of the tsf categories. This supports the concept of continuous change in plant community composition due to individualistic responses of species (Gleason 1926), rather that the Clemensian theory of plant succession and climax plant communities (Clements 1936).

CHAPTER 4

THE EFFECTS OF FIRE ON EPHEMERAL VEGETATION IN THE SONORAN DESERT

Introduction

The Arizona Upland Subdivision of the Sonoran Desert supports a spatial and temporal dynamic production of herbaceous biomass. Desert annuals are temporally responsive to high levels of climatic variation driven by rainfall (Venable and Pake 1999), and spatially distributed by micro-environmental heterogeneity (Schlesinger et al. 1996, Smith et al. 1997, Venable and Pake 1999). Both nitrogen and water are generally insufficient to support a homogeneous cover of vegetation in most parts of the Sonoran Desert (McAuliffe 1994, McClaran and Brady 1994, Venable and Pake 1999). However, nutrients are favorable in the soil under shrubs compared to open interspaces (Whysong and Heisler 1978, Szarek et al. 1982, Smith et al. 1997). The interaction of climatic and biological attributes creates a phenomenon that is an important function in some native Sonoran Desert ecosystems. This phenomenon is a functional source/sink relationship between the nutrient rich patches and the bare interspaces. The interspaces are sources of soil materials and runoff water while the patches serve as a sink of soil nutrients and a microclimate providing shade (Shachak and Lovett 1997).

The patchy arrangement of vegetation in some Sonoran Desert plant communities is not characteristic of fire dependent ecosystems, because in this desert ecosystem a continuous source of fuel is insufficient to promote the spread of fire. This characteristic, along with and the lack of fire-adapted plants in native plant communities, leads to the theory that fires were infrequent and thus unimportant in the long-term evolutionary history in most Sonoran Desert plant communities (Humphrey 1974, McLaughlin and Bowers 1982, Patten and Cave 1984, Rogers 1986, Smith et al. 1997, Barbour et al. 1999). The invasion of exotic grasses, especially red brome (*Bromus rubens*) appears to be changing the patchy arrangement of vegetation in some Arizona Upland Subdivision of the Sonoran Desert plant communities by filling in the

interspaces and changing the fire regime (Young and Evans 1973, D'Antonio and Vitousek 1992, Price 1997, Smith et al. 1997, Esque and Schwalbe in draft).

Most grasses are characterized as having fine leaves with large surface/volume ratios that can dry out quickly. This characteristic provides fuel to spread fires under a boarder range of conditions than do woody fuels and surface leaf litter (D'Antonio and Vitousek 1992). Moreover, grasses in the Sonoran Desert generally support standing dead material that remains after becoming decadent, whereas native forbs tend to disarticulate (Allen et al. 2001, Esque and Schwalbe in draft). Therefore, grasses provide a source of fuel for a longer period of time increasing the probability of fire ignition and spread in the Sonoran desert.

The invasion of red brome could set in motion a grass/fire cycle where it colonizes an area and provides the fine fuel necessary for the initiation and propagation of fire (D'Antonio and Vitousek 1992, Smith et al. 1997, Swetnam and Betancourt 1998). Because grasses support very little above–ground structural tissue, their post fire recovery is more rapid than native forb or shrub species, which promotes a further increase in susceptibility to fire. Parallel situations have been documented in semi-arid ecosystems where alien species have changed the fire regime. One of such has developed in some desert riparian regions of the Southwest, where the historical cottonwood-willow (*Populus-Salix*) gallery forests are being replaced by the exotic salt cedar (*Tamarix ramosissima*). This invasion, along with fire, stimulates a self-promoting fire cycle in a community-type that had limited historical exposure to fire (Brock 1994). Another situation occurs in the Intermountain West where researchers have documented that downy brome (*Bromus tectorum*) became established in inter-spaces between the shrubs and subsequently the fire-return time decreased from decades to less than 10 years (Sage 1996). The fire cycle set with downy brome now occurs at a greater frequency than the recovery time for the perennial native vegetation (Young and Evans 1973).

Similar interactions could occur in many Sonoran Desert plant communities primarily with an increase in the red brome (Rogers and Vint 1987, Smith et al. 1997). Perennials such as creosote bush (*Larrea tridentada*), bursage (*Ambrosia dumosa*), cholla and prickly pear (*Opunita*

spp), white ratany (*Krameria grayi*), palo verde (*Cercidium microphyllum*) and saguaro cactus (*Carnegiea gigantea*) suffer high rates of mortality and do not readily return to post burn communities (Rogers and Steel 1980, Cave and Patten 1984, Loftin 1987, Griffith 1991, Sweat 1995, Smith et al. 1997). Therefore, these plant communities could become dominated by red brome.

The effects of continuous stands of Red brome on the occurrence of fire in the Sonoran Desert has been documented, as well as the effects of fire on native perennial vegetation (Humphrey 1974, McLaughlin and Bowers 1982, Patten and Cave 1984, Rogers 1986, Rogers and Vint 1987, Smith et al. 1997, Barbour et al. 1999, Swantek et al. 1999, Esque and Schwalbe in draft). However, because of the high variability in climatic conditions, the effects of fire on the production of red brome and other ephemeral vegetation in the Sonoran Desert has not been well documented. The purpose of this study is to determine the effects of fire on the production of red brome and ephemeral vegetation in the Sonoran Desert.

Methods

Study Area

The study was conducted on five Sonoran Desert burn sites on the Tonto National Forest. The study sites and macro plots are the same as those described in Chapter III (page 43). The sites were selected based the time-since-fire (tsf) intervals: less than five years (5 tsf); five to fifteen years (5 – 10 tsf); fifteen to twenty years (15 – 20 tsf); twenty to twenty-five years (20 – 25 tsf) and repeated burns.

Field Data Collection

A random-systematic design (Barbour et al. 1999) was used to sample the production of herbaceous vegetation in burned and control plots in five burned areas in the Sonoran Desert. Five 100 m X 100 m (one hectare) macro plots were located within the burned area of each study site, and in adjacent control areas. Within each macro plot, four one hundred meter transects were randomly selected and four 1 m^2 micro-plots were randomly located along the 100 m

transects. The green weight of herbaceous vegetation was estimated in each micro plot. Fifty percent of the plots were clipped, fresh weighed, and recorded to provide a correction factor for the estimates. Then the clipped samples were oven dried at 50^0 C for 24 hours and then weighed to determine the oven dry weight (U.S. Forest Service 1999). The production of red brome was measured separately from the other herbaceous species.

The canopy cover of red brome, and other key Sonoran Desert plants, was measured in 100 plots on the River fire in the spring of 1998. The plots were located in four line transects from the Bush Highway North at a direction of 14 ° from true north. Each line consisted of 25 sample plots located 200 meters apart. An observation was made as to whether the area of the plot was burned or unburned and the location of each plot was recorded with GPS (Global Position System) units.

A modified two-dimension plot measurement was used to measure percent cover of shrubs, half shrubs and trees vegetation described by Daubenmire (1959). The cover of key species were estimated inside a 100 m^2 circular plot, and the cover for red brome was estimated by measuring cover in four 20 X 50 cm^2 rectangular frames. The readings for red brome were taken in each quadrant of the 100 m^2 circular plot for a total of 100 samples for each of the four transects. The key species measured are presented in Table 4.1.

Statistical Analysis

The paired student "t" test program of the SPSS Base 10.0 software was used to compare the vegetative production and cover between the control and burned treatments of each fire (study area). The pooled "t" test (Zar 1996) was used to compare the mean production between burned and control plots. The four plots in each of the treatment area served as replications in the herbaceous production sampling, and the four transects (consisting of 25 plots) served as replications in the sampling of red brome and key species cover. The pooled "t" test determined if there was a significant difference ($P = < 0.05$) in cover and production.

Table 4.1. Key species measured in each study plot to determine herbaceous plant production.

Scientific Name:	Common Name:
Abutilon palmeri Gray	superstition mallow
Amsinckia intermedia F.&M.	fiddle neck
Aristida purpurea Nutt.	purple three-awn
Asclepias subulata (Gray) Vail.	desert milk weed
Baileya multiradiata Harv.& Gray.	wild marigold
Brassica campestris L.	field mustard
Bromus rubens L.	red brome
Camissonia brevipes Gray Raven	yellow cups
Eriastrum diffusum (Gray) Mason	miniature wool star
Eriogonum palmerianum Reveal.	arroyo lupine
Eschscholtzia mexicana Greene.	mexican poppy
Lupinus sparsiforus Benth.	desert lupine
Lupinus succulentas Dougl.	arroyo lupine
Orthocarpus purpurascens Benth.	owl clover
Penstemon pseudospectabilis Jones.	mohave beard tongue
Phacelia distans Benth.	paper flower
Polanisia dodecandra (L.) DC.	clammy weed
Sphaeralcea ambigua Gray.	desert mallow
Verbena goodingii Briq.	gooding verbena

Results and Discussion

Herbaceous production

During 2001 there was very little production of red brome ($P = < 0.05$) measured in any of the plots. Red brome was observed in small isolated patches, within each plot, where the micro-environmental conditions maintained moist conditions. The lack of production red brome was a puzzling result since the growing period (spring of 2001) was preceded by above average fall and winter moisture, and the production of native annuals and flowers was outstanding. The low production of red brome and high production other annual plants was consistently observed in the Arizona Upland Subdivision of the Sonoran desert (personal communications with personnel from USGS, University of Arizona, Saguaro National Park, Organ Pipe National Park, U.S. Forest Service). Hunter (1991) found that native ephemerals behaved somewhat differently than red brome in response to moisture on the Nevada Test Site. He reported that following two very hot years 1971 and 1972 the native species responded immediately after a wet spring in 1973. While red brome population required two years to reach its previous density. This interaction of red brome and native ephemerals indicates that the native seeds are better adapted to severe drought, while red brome appears to reproduce better in the normal years (Hunter 1991). The low production of red brome in the spring of 2001 can be explained by the lack of an seed source. The most recent year observed to produced a large crop of red brome was 1998. The fall and winter seasons of 1999 and 2000 were very dry and there was below average production of red brome and other herbaceous vegetation. The seed viability of red brome decreases rapidly over the first year after seeds are dispersed (Wu and Jain 1979). Seed viability is almost 100 percent during the initial fall, however, seed carry-over from one year to the next is less than 2 percent (Wu and Jain 1979). Since red brome did not produce seeds for a 2 year period (1999 and 2000) it is intuitive to expect low production in 2001. Coincidental with the low production of red brome, in 2001, was an exceptionally low occurrence of fires in the Sonoran Desert in the Sonoran

Desert on the Tonto National Forest, even though there was an above average production of other annuals.

Production of herbaceous vegetation was significantly greater ($P = < 0.05$) in the control plots of the River fire (5 years tsf) and the Bush Highway fire (repeated fires) (Table 4.2). However, there was no a significant difference in the production on the Vista fire (7 years tsf). The fires with a longer time-since-fire, Massacre (17 years tsf) and Siphon (21 years tsf) supported greater production of herbaceous vegetation in the burned plots (Table 4.2).

The production of herbaceous vegetation is highly correlated with the seasonal distribution of precipitation and soil available moisture (Mulroy and Rundel 1977). Factors that influence water availability are: interception of rainfall and runoff by standing vegetation (DeBano et al. 1998), evapotransporation and growth form of shrubs and trees Gottfried et al. 1999), DeBano et al. 1998), and N distribution (Whysong and Heisler 1978, Shiqiang et al. 2001). DeBano et al. (1998) described that vegetative canopy and litter can be lost completely in severe fires and, as a result, comparatively little interception of precipitation occurs. However, fire that modifies the composition and structure of vegetation by removing foliar volume can result in less evapotransporation (ET) losses from a watershed (DeBano et al. 1998). Fire that results in replacement of deep-rooted, high-profile trees and shrubs by shallow rooted, low profile herbaceous plants is also likely to reduced ET losses.

Fire can lower the ET loss by removing vegetation which can leave more water in the soil at the end of the growing season (DeBano 1998). Lower ET losses, in turn, leaves more water in the soil at the end of the growing season. Gottfried et al. (2001, in draft) conducted a study in oak woodlands in Southwestern US and Israel to determine the evapotransporation of mature versus harvested oak trees. Evaporation was higher in mature trees than cut trees. However, the evaporation over one hectare was higher in the cut areas due to the increased number of sprouts (Gotfried et al. 2001, in draft).

With the documentation of the effects of fire on the ET on other vegetation types, one could surmise that greater production occurred in control plots of the fires with the shorter tsf (eg.

Table 4.2. Comparison of the production of herbaceous vegetation in the burned versus the unburned plots.

Fire name	Control (kg/hectare ± SE)	Burned (kg/hectare ± SE)	Difference (kg/hectare ± SE)
River (5 years tsf)	1088 ± 49	642 ± 33	446 ± 46 *
Vista (7 years tsf)	306 ± 60	348 ± 86	-42 ± 42
Bush Highway (repeated burns)	614 ± 131	384 ± 68	230 ± 199
Massacre (17 years tsf)	475 ± 18	647 ± 28	-172 ± 29 *
Siphon (21 years tsf)	286 ± 26	409 ± 32	- 123 ± 21 *

* significant (P = < 0.05)

River fire, 5 years tsf) because moisture could be lacking with the greater run-off in the burned areas. The burned areas of the River fire supported very little recovery of perennial plants, and ground cover was significantly greater in the control plots (Chapter 3). The factor controlling the production of herbaceous vegetation in the River fire appeared to be the presence of trees, shrubs and half shrubs which provided a micro-climate for higher production of herbaceous vegetation in the control plots. However, more herbaceous production was measured in the burned plots than the control plots of the Massacre (17 years tsf) and the Siphon (21 years tsf). The factor that influenced the production of herbaceous vegetation in these fires could be ET in the control plots. There is a smaller difference in canopy cover between the burned and control plots of these fires (Chapter 3). Many perennial shrubs and half shrubs have recovered in the burned areas and should be effectively intercepting moisture run-off. However, the control plots still support larger trees and cacti, which could cause higher ET and less soil moisture available for the production of herbaceous vegetation.

The temporal patterns of soil N (NH_4^+ and NO_3^-) could be a factor influencing the difference in herbaceous production over time. Although the total soil N pools are not generally affected by fires (Shiqiang et al. 2001, Whysong and Heisler 1978), elevated soil NH_4^+ generally persists for several months after fire (Covington and Sacket 1986, DeBano et al. 1998) and then declines to a pre-fire level one year after fire (Shiqiang et al. 2001, DeBano et al. 1998) because of increased nitrification, leaching, microbial immobilization, and plant uptake (Evans et al. 2001). The dynamics of soil N, time and herbaceous production could explain the lower production of herbaceous production in the burned area of the River fire (5 years tsf) and the no significant difference in the Vista fire (7 years tsf). The soil N (NH_4^+ and NO_3^-) could have increased immediately after fire and then declined to the pre-fire condition after one year. Therefore, the factor that depressed herbaceous production was probably increased aridity of the site because of lack of shrubs and treelike species (Balling et al. 1998).

The Bush Highway fire (repeated burns) plots contained less canopy cover from shrubs and trees, therefore there was less shaded micorclimate than the adjacent control plots. The native Sonoran plant community has been replaced by purple three-awn (*Aristida purpurea*) six-weeks fescue (*Festuca octoflora*), six-weeks three-awn (*Aristida adscensionis*), Mediterranean grass (*Schismus barbatus*) and red brome (*Bromus rubens*). The observed conversion to grasses and drying of the site is consistent with the findings of D'Antonio and Vitousek (1992). The greater herbaceous production in the control plots can be explained by a more favorable microsite among the shrubs and trees in the unburned areas.

Canopy Cover

The canopy cover of the key Sonoran Desert plants measured in 1998 was significantly greater ($P = < 0.05$) in the control plots (17.5%) compared to the burned plots (2.6%, Table 4.3). The decreased in canopy cover in the 1998 burned plots were consistent with the effects of fire on canopy cover in the 1999 study (Chapter III).

There was not a significant difference ($P = < 0.05$) in the canopy cover of red brome between the burned and unburned areas of the River fire in 1998. There is likely an interaction between the competition for light, moisture and nutrients that would be difficult to quantify. During 1998, a high moisture winter, red brome grew both in the shade of shrubs and in the open areas. During low moisture years one would expect red brome to grow more under the protection of shrubs and half shrubs.

Conclusion

Fire decreased the production of herbaceous vegetation in the more recent fires. The factors that influenced the production of herbaceous vegetation in the River fire (5 years tsf) appeared to be the presence of trees, shrubs and half shrubs which provided a micro climate for higher production of herbaceous vegetation in the control plots. However, more herbaceous production was measured in the burned plots than the control plots of the Massacre (17 years tsf) and the Siphon (21 years tsf). The factor that influenced the production of herbaceous vegetation

Table 4.3. Comparison of the cover of red brome and key species in the burned versus the unburned plots of the River fire in 1998.

	Control (%) ± SE)	Burned (%) ± SE)	Difference (%) ± SE)
Key Species	17.5 ± 3.3	2.6 ± 0.7	14.9 ± 2.8 *
Bromus rubens	18.5 ± 8.0	17.4 ± 3.0	1.1 ± 7.0

* significant (P = < 0.05)

in these fires could be the ET in the control plots. Perennial shrubs and half shrubs have recovered in the burned areas of the Massacre (17 years tsf) and the Siphon (21 years tsf) fires which appears to intercept moisture run-off and improve infiltration. However, the control plots still support larger trees and cacti, which could cause higher ET and less soil moisture available for the production of herbaceous vegetation.

The production of red brome did not increase during one moist fall and winter, so it appears that more than one moist winter is needed for an above average crop of red brome (Hunter 1991).

More research is needed to determine the effects of recovery of perennial shrubs and trees on the dynamics of ET, available soil moisture and soil N on the production of herbaceous vegetation, especially for red brome.

CHAPTER 5

MANAGEMENT IMPLICATIONS OF FIRE ON SONORAN DESERT PLANT COMMUNITIES

Proactive management is needed to prevent unnatural frequent, large fires that cause long-term changes in the Sonoran Desert vegetation. To effectively manage scarce resources, it is important for managers to understand the factors that contribute to critical fire years in the Sonoran Desert. Anthropogenic factors that introduce the ignition source to vegetation can be intensely managed during years when high production of winter ephemeral plants occur. Heavy winter ephemeral plant production has historically depended on the amount of rainfall that falls during the current winter and the previous winter.

New highway designs have appeared to have reduced the occurrence of fire ignition from vehicles by increasing the width of the road shoulder, and planting sparsely spaced native vegetation in the right-of-way. Since the trend in the occurrence of fires has increased during the past 45 years, it is important that actions be taken to reverse that trend. One possible action would be to intensely manage vegetation on the highway shoulders, during the spring following the two previous and three wet winters. Actions could include the use of a pre-emergent herbicide, or closely mowing the road shoulders. Other considerations could be the closing or restriction of off-road-vehicle trails and campground use during this critical season.

The use of fire or livestock grazing should not be eliminated from consideration for managing critical corridors, but caution should be used in their applications. With the premise that both fire and large animal herbivory were not part of the ecology and evolutionary history of the Sonoran Desert (Smith et al. 1997,), there is a risk of type conversion of the native vegetation (Rogers and Steele 1980, Cave and Patten 1984, Rogers 1985, Abou-Haidar 1989, Smith et al. 1997, Martin 1999, Wilson et al. 2000). Invasive exotic plant species have altered succession trajectories in some plant communities. Burning in the Sonoran Desert appears to result in the conversion of the sites to exotic vegetation such as *Bromus rubens* (red brome). Prescribed fire in the Sonoran Desert should only be considered if post-fire restoration treatments are planned. Intense short-

term grazing would be needed to reduce the volume of fuels, but long-term grazing also inhibits the regeneration of native Sonoran Desert vegetation (Abou-Haidar 1989, Smith et al. 1997). Grazing to reduce fuel should only be applied in critical corridors to protect adjacent Sonoran Desert vegetation from fire ignition sources.

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APPENDIX A

NATIONAL CLIMATIC DATA CENTER (NCDC) INFORMATION ON THE WEATHER STATIONS FROM WHICH THE PRECIPITATION DATA WAS TAKEN

Weather Station	Location	Climate Division	COOP ID	In Service	Elevation	Latitude/Longitude
Bartlett Dam	Bartlett Lake, AZ	AZ-06-South Central	020632	July 1, 1948 to Present	502.9m (1649.5') above sea level	33°49'N/111° 39'W
Miami	Miami, AZ	AZ-04-East Central	025512	July 1, 1948 to Present	1085.1m (3559.1') above sea level	33°24'N/110° 52'W
Roosevelt 1 WNW	Roosevelt, AZ	AZ-04-East Central	027281	July 1, 1948 to Present	672.1m (2204.5') above sea level	33°40'N/111° 09'W
Stewart Mountain	Stewart Mountain, AZ	AZ-06-South Central	027214	July 1, 1948 to Present	433.4m (1421.6') above sea level	33° 33'N/111° 32'W

APPENDIX B.

MONTHLY PRECIPITATION FROM THE NOAA (NCDC). MONTHLY TOTALS FROM THE BARTLETT, STEWART MOUNTAIN, AND ROOSEVELT, ARIZONA STATIONS

Year	January	February	March	April	May	June	July	August	September	October	November	December	Total Annual Precipitation
1955	74.68	2.79	.00	2.03	1.44	37.76	113.96	98.47	2.62	1.78	11.60	20.40	367.54
1956	32.43	24.21	.00	6.86	1.44	2.96	39.88	9.40	2.79	21.51	.00	2.71	144.19
1957	133.27	14.05	25.15	2.54	15.24	11.68	22.27	28.62	.00	86.87	5.25	10.24	355.18
1958	.34	35.48	74.59	23.71	4.83	5.67	5.00	40.13	92.54	22.86	21.67	.00	326.81
1959	6.18	40.98	.00	1.19	1.27	4.06	13.04	72.47	6.52	107.27	16.85	138.26	408.09
1960	58.50	7.87	17.10	.00	2.54	1.27	36.24	30.65	22.10	41.57	5.00	2.03	224.87
1961	14.65	1.02	24.47	.08	.00	6.52	21.25	33.61	34.29	8.72	7.03	68.07	219.71
1962	52.41	46.14	34.46	.76	3.05	.25	9.06	7.20	39.45	6.86	15.92	33.44	249.00
1963	23.88	41.32	18.03	12.11	.00	.00	3.64	157.65	16.26	23.45	49.61	3.39	349.33
1964	13.55	.00	24.98	9.91	.00	.00	35.73	76.54	36.58	8.97	32.34	28.96	267.55
1965	69.34	48.18	50.21	53.51	7.37	5.16	22.44	11.85	27.18	11.26	61.04	208.11	575.65
1966	15.49	32.68	8.38	.17	.00	4.49	7.62	43.52	43.52	20.32	21.25	35.39	232.83
1967	9.14	.00	23.03	16.34	4.83	8.81	72.22	33.27	39.54	2.79	49.53	162.14	421.64
1968	20.32	30.82	44.37	3.56	.17	.00	44.87	71.04	.00	19.30	47.84	41.66	323.93
1969	57.40	33.61	28.28	3.47	21.34	.00	28.36	51.05	28.53	14.73	34.88	21.59	323.26
1970	6.94	13.38	68.75	9.06	.08	.00	31.50	15.07	98.98	17.53	4.06	16.76	282.11
1971	7.03	15.24	.00	8.97	.00	.00	5.76	61.55	53.51	63.84	1.95	27.77	245.62
1972	.00	.00	.00	.00	2.37	61.81	17.95	24.38	12.19	187.54	49.28	67.39	422.91
1973	11.09	73.74	104.99	.17	23.88	9.48	33.70	15.92	.00	.00	33.95	.00	306.92
1974	50.72	.59	42.33	3.64	.00	.00	27.52	14.99	22.18	80.69	7.70	24.47	274.83
1975	8.30	32.34	56.30	35.39	.93	.00	27.43	9.65	36.91	5.00	41.40	32.43	286.09
1976	3.47	77.22	16.85	38.86	17.53	.00	24.47	15.58	48.68	24.38	4.74	14.82	286.60
1977	55.03	59.44	12.95	7.87	6.60	.76	10.92	39.37	45.72	21.42	12.95	15.83	288.88
1978	102.95	117.60	175.18	13.46	9.91	11.77	47.07	44.87	9.48	29.55	95.84	136.65	794.34
1979	131.06	10.33	83.82	4.40	40.89	1.52	10.41	33.02	2.03	14.31	15.75	9.74	357.29
1980	122.60	174.16	53.42	15.83	4.91	3.13	28.36	37.08	18.71	6.77	.00	8.89	473.88
1981	18.12	32.43	53.76	16.26	13.63	4.74	44.11	21.17	26.59	30.14	51.14	.17	312.25
1982	60.11	41.15	70.36	.25	33.44	.00	32.85	37.17	35.73	.51	93.22	67.39	472.19
1983	49.02	67.99	124.63	17.61	1.10	.00	20.40	69.34	91.78	52.83	30.48	50.21	575.39
1984	11.18	.00	.00	24.55	4.32	7.11	85.77	54.19	92.20	35.98	44.87	129.12	489.29

Year	January	February	March	April	May	June	July	August	September	October	November	December	Total Annual Precipitation
1985	45.72	27.86	32.85	16.76	.17	.34	34.12	21.08	78.32	45.80	83.74	25.91	412.67
1986	7.96	57.32	73.91	1.52	1.02	8.30	63.16	56.64	20.15	51.14	36.91	55.12	433.15
1987	43.18	69.43	13.97	7.45	15.16	1.52	9.14	42.08	9.91	33.61	54.61	42.16	342.22
1988	53.17	17.10	3.73	48.01	.00	4.32	43.69	83.31	2.88	43.69	19.64	7.37	326.90
1989	59.35	8.47	49.95	.00	3.47	.00	41.83	32.68	8.64	26.59	7.70	18.54	257.22
1990	31.67	33.02	44.20	22.86	6.77	3.64	49.70	75.35	41.99	.68	32.94	61.04	403.86
1991	34.71	22.27	147.07	.00	.25	.68	7.87	37.08	44.45	23.03	41.23	80.01	438.66
1992	64.94	45.97	135.64	24.81	59.77	4.91	60.71	121.07	8.04	18.54	3.73	140.04	688.17
1993	241.81	107.61	62.31	.08	4.74	.59	4.66	89.07	8.13	31.16	115.74	2.79	668.70
1994	5.08	57.74	46.82	17.27	17.86	.08	29.46	15.24	19.56	19.22	41.74	86.11	356.19
1995	112.69	27.01	75.44	10.33	4.15	.00	9.74	50.21	42.84	.00	26.67	.85	359.92
1996	.93	39.54	14.05	.00	.00	.17	39.54	24.98	61.98	10.50	14.05	4.32	210.06
1997	72.14	47.24	1.10	14.73	4.32	.34	.42	43.52	19.05	18.20	8.72	72.05	301.84
1998	38.95	142.92	71.12	20.57	1.86	.00	38.44	39.71	36.41	43.35	28.19	20.83	482.35
1999	3.98	12.62	2.12	58.67	.25	.00	81.87	61.04	53.26	.00	.00	.25	274.07
Mean	45.23	39.79	44.68	12.79	7.62	4.75	31.96	45.59	32.05	29.65	30.73	44.34	369.20

APPENDIX C

ANTHROPOGENIC FCTORS EVALUADTE TO DETERMINE THEIR EFFECT ON NUMBER OF FIRES AND HECTARES BURNED ANNUALLY

Year	Highway traffic on SH60 + SH87	Population in Maricopa County	Hectares Burned	Number of Fires
1955	2725	509650	.12	3
1956	2989	540422	492.31	9
1957	3346	571194	45.73	3
1958	3370	601966	285.80	21
1959	3866	632738	3397.17	12
1960	4001	663510	4.82	11
1961	4082	694281	30.64	9
1962	4415	725053	20.92	8
1963	4591	755825	9.59	15
1964	4738	786597	14.25	8
1965	5073	817369	64.71	16
1966	5456	848141	726.91	33
1967	4988	878913	7.57	8
1968	5276	909685	3.93	5
1969	6045	940457	557.55	44
1970	6622	971228	292.31	33
1971	6983	1026400	44.21	15
1972	8276	1087200	1.00	16
1973	8800	1156700	387.39	80
1974	7100	1217400	1018.23	53
1975	8700	1253900	358.43	93
1976	9700	1280000	2949.41	92
1977	12000	1329800	63.13	49
1978	12400	1388900	35.61	59
1979	8000	1456800	16198.70	133
1980	8200	1509175	9297.45	218
1981	9800	1566036	382.44	141
1982	10100	1611847	100.20	97
1983	10600	1663973	1912.04	133
1984	10600	1736952	395.43	106
1985	11900	1828748	193.44	120
1986	11900	1905504	146.09	121
1987	12400	1991400	261.84	108
1988	13200	2048441	3251.32	189
1989	15100	2101787	117.77	82
1990	12400	2122101	21.45	43
1991	12900	2179975	457.71	70
1992	14600	2233700	647.51	131
1993	16439	2291200	956.76	153
1994	13282	2355900	1976.97	126
1995	15876	2528700	6374.54	125
1996	15749	2634625	39.09	65
1997	14631	2720575	9.11	37
1998	15075	2806100	350.04	94
1999	15800	2879500	114.37	117

APPENDIX D.

SUMMARY OF CLIMATIC VARIABLES, HECTARES BURNED AND NUMBER OF FIRES IN THE SONORAN DESERT ON THE TONTO NATIONAL FOREST FROM 1995 THROUGH 1999

Year	Total Annual Precipitation (mm)	Winter Precipitation (mm)	Summer Precipitation (mm)	Previous Summer + Winter Precipitation (mm)	Previous Winter 2 + Winter Precipitation (mm)	Previous Winters + Winter Precipitation (mm)	Previous Winter + Previous Summer + Winter Precipitation (mm)	Hectares Burned (mm)	Number of Fires (mm)
1955	367.54	77.58	252.81	206.10	163.18	239.21	413.37	.12	3
1956	144.19	59.35	55.03	309.54	136.93	222.53	189.17	492.31	9
1957	355.18	157.56	62.57	209.80	216.92	294.50	279.48	45.73	3
1958	326.81	35.81	143.34	98.38	193.38	252.73	244.18	285.80	21
1959	408.09	185.42	96.10	236.22	221.23	378.80	310.81	3397.17	12
1960	224.87	68.41	90.25	157.99	253.83	289.64	321.99	4.82	11
1961	219.71	83.74	95.67	151.89	152.15	337.57	213.53	30.64	9
1962	249.00	132.00	55.96	193.38	215.73	284.14	232.24	20.92	8
1963	349.33	68.58	177.55	85.09	200.58	284.31	361.87	9.59	15
1964	267.55	42.50	148.84	203.79	111.08	243.08	223.35	14.25	8
1965	575.65	325.63	66.63	437.90	368.13	436.71	407.59	64.71	16
1966	232.83	83.57	99.14	123.02	409.19	451.70	464.82	726.91	33
1967	421.64	171.28	153.84	226.91	254.85	580.47	369.15	7.57	8
1968	323.93	92.79	115.91	207.09	264.08	347.64	379.98	3.93	5
1969	323.26	112.61	107.95	228.52	205.40	376.68	284.82	557.55	44
1970	282.11	37.08	145.54	116.50	149.69	242.49	196.26	292.31	33
1971	245.62	50.04	120.82	96.60	87.12	199.73	154.43	44.21	15
1972	422.91	67.39	116.33	134.70	117.43	154.52	221.57	1.00	16
1973	306.92	84.84	59.10	188.98	152.23	202.27	211.33	387.39	80
1974	274.83	75.78	64.69	134.87	160.61	228.01	203.12	1018.23	53
1975	286.09	73.07	74.00	115.57	148.84	233.68	185.93	358.43	93
1976	286.60	95.50	88.73	132.59	168.57	244.35	208.62	2949.41	92
1977	288.88	130.30	96.77	170.35	225.81	298.87	276.86	63.13	49
1978	794.34	357.21	113.20	408.26	487.51	583.01	591.23	35.61	59
1979	357.29	151.13	46.99	254.85	508.34	638.64	553.30	16198.70	133
1980	473.88	305.65	87.29	350.60	456.78	813.99	525.36	9297.45	218
1981	312.25	50.72	96.60	119.30	356.36	507.49	426.38	382.44	141
1982	472.19	168.66	105.75	238.68	219.37	525.02	289.39	100.20	97
1983	575.39	167.22	181.53	237.24	335.87	386.59	425.62	1912.04	133
1984	489.29	140.29	239.27	230.04	307.51	476.17	454.58	395.43	106

Year	Total Annual Precipitation (mm)	Winter Precipitation (mm)	Summer Precipitation (mm)	Previous Summer + Winter Precipitation (mm)	Previous Winter 2 + Winter Precipitation (mm)	Previous Winters + Winter Precipitation (mm)	Previous Winter + Previous Summer + Winter Precipitation (mm)	Hectares Burned (mm)	Number of Fires (mm)
1985	412.67	99.48	133.86	246.55	239.78	406.99	295.32	193.44	120
1986	433.15	120.40	148.25	175.94	219.88	360.17	347.98	146.09	121
1987	342.22	154.77	62.65	282.87	275.17	374.65	327.91	261.84	108
1988	326.90	77.64	134.20	130.39	232.41	352.81	363.73	3251.32	189
1989	257.22	86.36	83.14	217.68	164.00	318.77	238.51	117.77	82
1990	403.86	125.73	170.69	200.24	212.09	289.73	340.78	21.45	43
1991	438.66	136.99	90.09	265.68	262.72	349.08	308.36	457.71	70
1992	688.17	250.95	194.73	296.59	387.94	513.67	574.63	647.51	131
1993	668.70	352.21	102.45	538.90	603.17	740.16	697.48	956.76	153
1994	356.19	148.93	64.35	243.25	501.14	752.09	545.93	1976.97	126
1995	359.92	140.55	102.79	185.34	289.48	641.69	349.42	6374.54	125
1996	210.06	44.79	126.66	104.73	185.34	334.26	250.02	39.09	65
1997	301.84	191.43	63.33	256.12	236.22	376.77	280.50	9.11	37
1998	482.35	202.69	114.55	246.97	394.12	438.91	472.27	350.04	94
1999	274.07	16.85	196.17	95.00	219.54	410.97	362.46	114.37	117
Mean	369.20	128.92	82.31	210.91	259.37	387.01	351.68	1200.36	68.98
(SE)	(!19.88)	(!12.35)	(!6.77)	(!17.68)	(!17.57)	(!38.18)	(!33.03)	(!430.95)	(!8.34)

APPENDIX E

VARIABLES EXCLUDED IN THE STEPWISE MULTIPLE REGRESSION PROCESS EVALUATING THE INFLUENCE OF NINE VARIABLES ON NUMBER OF FIRES AND HECTARES BURNED

Model		Beta In	*t*	Sig.	Partial Correlation	Collinearity Statistics Tolerance
		NUMBER OF FIRES				
1	Total Annual Precipitation	.147	1.230	.226	.186	.890
	Summer Precipitation	-.001	-.010	.992	-.002	.999
	Winter Precipitation	.135	1.149	.257	.175	.932
	Consecutive summer and winter precipitation	.105	.901	.373	.138	.960
	Two consecutive winters precipitation	.340	3.056	.004	.426	.876
	Three consecutive winters precipitation	.416	3.885	.000	.514	.849
	Consecutive winter, Summer and Winter Precipitation	.316	2.813	.007	.398	.884
	Population in Maricopa County	.183	.458	.649	.071	8.231E-02
2	Total Annual Precipitation	-.050	-.422	.675	-.066	.702
	Summer Precipitation	.003	.035	.973	.005	.999
	Winter Precipitation	-.194	-1.490	.144	-.227	.559
	Consecutive Summer and Winter Precipitation	-.158	-1.319	.194	-.202	.671
	Two consecutive winters precipitation	-.018	-.093	.927	-.014	.254
	Consecutive Winter, Summer, Winter Precipitation	-.009	-.054	.957	-.008	.342
	Population in Maricopa County	-.041	-.116	.908	-.018	8.001E-02
		HECTARES BURNED				
3	Total Annual Precipitation	-.282	-1.856	.070	-.275	.721
	Summer Precipitation	-.159	-1.208	.234	-.183	1.000
	Winter Precipitation	-.217	-1.235	.224	-.187	.559
	Consecutive Summer and Winter Precipitation	-.204	-1.270	.211	-.192	.671
	Two consecutive winters precipitation	.001	.005	.996	.001	.254
	Consecutive Winter, Summer, Winter Precipitation	-.166	-.731	.469	-.112	.343
	Population in Maricopa County	-.134	-.920	.363	-.141	.827
	Highway traffic on SH_60 + SH_87	-.170	-1.190	.241	-.181	.849